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A SYNTHESIS OF CLIMATOLOGICAL STUDIES
IN ALBERTA FROM 1975 to 1986

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IN ALBERTA FROM 1975 TO 1986

by

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Alberta Environment

1990

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ABSTRACT

About 250 climatological studies with direct application to the province of Alberta are selected and compiled from the period 1975 to 1986, and, from these, an attempt is made to synthesize the results and progress made in several fields of specialization. The total number of studies of Alberta's climate in relation to agriculture, forestry, and water resources are similar to those for an earlier period 1957 to 1969, but some changes in focus appear. The period 1975 to 1986 features significant increases in work on climate in relation to agricultural and forest land classification, urban climates, and the climate of the Athabasca oil sands region. New, comprehensive climatologies appear for Banff and Jasper National Parks, Calgary, Edmonton, and Kananaskis. New technologies such as Doppler and monostatic acoustic sounders, minisondes, automatic lightning detectors, and automatic digitization of weather radar echoes enter research activities and find new applications. Modest groundwork occurs for solar and wind energy applications. On the other hand, tourism and recreation, construction, transportation, and urban planning receive little research attention. The first studies of possible impacts of future climate change in Alberta emerge in 1975 to 1986. Climate change impact assessment techniques need to demonstrate considerable predictive skill before they can be applied convincingly to new climate scenarios for program planning. The need for more and better climate data continues, but the need continues also for improved planning of data acquisition systems and for incorporating multiple uses into observation program planning. Some evidence is found of improved understanding and communication between climate researchers and users of climate research results but much more remains to be done. Provincial interdisciplinary committees play a very important function in this regard and deserve recognition.



1. INTRODUCTION

The purposes of this report were to compile and summarize the climate and climate-related researches that were reported during the period 1975 to 1986 for Alberta, Canada. The report is divided into six sections. Section 2 includes a general discussion of Alberta's climate classification systems, followed by regional climatologies and climate station networks in the province. Section 3, on physical climatology, includes studies of solar radiation, precipitation, chinooks, and severe summer weather. Section 4 looks at applications of climatology in the resource sectors of agriculture, forestry, and water, with special attention to mapping of areas suitable for agriculture, assessment of forest biomass productivity, and calculation of evapotranspiration. Urban climate studies, and some discussion of the impacts of climate on recreation and tourism, close the section. Possible effects of future climate changes on agriculture and forestry, based on the very few studies that were completed prior to 1987, are described in Section 5. A summary and overview of climate research in Alberta in the period 1975 to 1986 completes the report.

The economy of Alberta is based largely on a rich heritage of natural resources. Albertans have long recognized that the past and present climate have influenced, and will continue to influence, the development of these natural resources. The major resource industries of agriculture and forestry operate near the economic margin. A small change in climate could be significantly detrimental, or beneficial, to Alberta's economy. The knowledge and understanding of climate and its

relationship to our resource base, with or without climate change, are crucial for optimum operation and maximum productivity of our economic sectors.

There is a growing awareness and understanding that atmospheric trace gases, such as carbon dioxide, play an important role in controlling the earth's heat balance, and in maintaining average surface temperatures at current levels. Changes in the atmospheric concentrations of trace gases, and the associated "greenhouse effect", have been the subject of scientific discussions at least since 1861 (Tyndall 1861; Arrhenius 1896; Chamberlain 1899). Such discussions became much more frequent following observations of simultaneous increases in global temperature and carbon dioxide concentrations in the early decades of this century. During the last decade, climate change and variability and their impact on humans and their environment have received major attention from scientists because of implications for the future (National Research Council 1982; World Meteorological Organization 1984; Postel 1986; Glantz et al. 1987; Chen and Parry 1987). Large research programs, such as the World Climate Research Program, and the Canadian Climate Program, have been activated to improve our understanding of climate, climate change processes, and our influence on global climate. These programs are illuminating the possible direct and indirect impacts of climate change on food production, water management, energy production, agriculture, forestry, human health, and other activities.

The first comprehensive study of observed climatic changes in Alberta and the other Prairie Provinces was that of Longley (1977). He

included concise descriptions of the most important theories of climatic change and pointed out that most cannot explain the climate variations observed in recent millenia. As for the future he concluded that, at the time of writing, the climate of the past 50 years is our best guide to what we may expect in coming years. The status of the impacts of climate change and variability on Alberta's resources and environment from a broad perspective was summarized by Leggat et al. (1981).

A bibliography of over 250 references was compiled from literature searches and from responses to requests submitted to researchers and managers. Extensive use was made of author's abstracts, results, summaries, and conclusions. Special mention must be made of the important contributions made to this report by the Alberta Climatological Association through its annual proceedings, minutes, and bibliographies (Alberta Climatological Association 1977, 1978, 1980a, 1980b, 1981, 1982, 1983, 1984, 1985, 1986). A few pre-1975 references were included because they were useful for background discussion, or because they were parts of major research projects that were accomplished primarily in the period under study. Three 1987 references were cited for background discussion, and one because it was a minor revision of a work that appeared in 1986.

In a synthesis of this nature, it is impossible to be completely objective in the selection of research studies to be included. It can be argued, for example, that almost all hydrological and glaciological works

have a climate¹-related component, and the same could be said of many meteorological studies. We offer our apologies to those whose work was missed, inadequately described, or misinterpreted in this report. Fortunately, other summaries and bibliographies exist. In Canada, we have the annual Canadian Geophysical Bulletin which includes summaries and bibliographies of work on meteorology and atmospheric science, oceanography, glaciology, aeronomy, isotope studies, geochronology, and hydrology. The latest issue was Canadian National Committee for the International Union of Geodesy and Geophysics (1987). The Bibliography of Canadian Climate comprises nearly 5000 references on Canadian climate dating back to 1763. The fourth and most recent volume was compiled by Phillips (1983). Entries from the second of these volumes, with additions, appeared in the Bibliography of Climatology for the Prairie Provinces 1957-1969 which was prepared by Longley and Powell (1971). A comprehensive bibliography of weather modification and related topics in Alberta was compiled recently by Wojtiw (1986c).

¹ Before undertaking any review of climate, it is important to distinguish the subtle difference between "climate" and "weather". These terms are often used interchangeably. "Weather" is an instantaneous description of the atmosphere, as defined by the measurement of meteorological variables, and the processes responsible for its present state. For the purposes of this review, "climate" refers to the summary conditions of the atmosphere for a given time period. A complete description of climate requires specification of the frequency distributions of unit variables as well as joint frequency distributions of multiple variables. Means, variances, covariances, and extreme values are important but incomplete parts of this knowledge. The spatial scales of climate range from global and synoptic (weather-map) through the mesoscale of, for example, a chinook, to the microscale of root and leaf environments. Time scales of climate also vary enormously from geologic to hourly or seasonal scales.

The reader is reminded that not all of the reports and publications mentioned in this synthesis have been subjected to external peer review. In particular, some government agency and consultant reports as well as most papers described as having been presented at meetings, as preprints, or as having appeared in proceedings of meetings, were not subjected to such review.

2. CLIMATOLOGY IN ALBERTA

Numerous studies on climate classification systems, and regional climatologies of Alberta, have been carried out to gain an understanding of regional climate with respect to resource development capability. A general discussion and synthesis of the available information are provided in the ensuing sections.

2.1 CLIMATE CLASSIFICATION SYSTEMS

There have been several attempts to classify the climates of Alberta and to define climate regions within the province. According to the classic climate classification scheme, named after Köppen, a German climatologist, Alberta falls primarily into the microthermal (D) or cool temperate zone with polar climates (E) prevailing in the mountain regions, and dry climates or steppes (B) in the southeast (Longley 1972). This classification, however, fails to describe adequately the climate zones of the province.

Historically in land classification work, climate has been inferred from vegetation and soils. Attempts to assess the inherent value of land for use by landuse managers led to the development of an integrated appraisal system, the ecological land survey. An ecoregion is an area characterized by a distinctive regional climate as expressed by vegetation (Subcommittee on Biophysical Land Classification 1969). In Alberta, there are three ecoprovinces: Boreal, Prairie, and Cordilleran. Recurring vegetation, soil, and moisture sequences produce 12 ecoregions within these boundaries (Strong and Leggat 1981). A few of

the climate parameters listed for the classification process are mean monthly temperature, freeze-free period, total precipitation, number of days with chinooks, and maximum depth or snowcover. In this study, each ecoregion in Alberta was mapped and described in terms of climate, vegetation, soils, and present uses. Each was then assessed in terms of its potential for agriculture, forestry, recreation, and ungulates.

A classification system for forest management strategies including stand establishment studies, tree improvement and breeding trials, fire protection, and hazard delineation for disease and insects was needed. This led to a series of research reports on climate classification published by the Northern Forest Research Centre (MacIver, Holland, and Powell 1972; Powell and MacIver 1976, 1977, 1978).

Daily temperature and precipitation data collected from 54 stations for the period 1954 to 1968 were used as input variables in a factor analysis model. Factor analysis is a statistical technique to reduce large numbers of interrelated input variables to a smaller number of more nearly independent factors. With this technique, 13 climatic regions were delineated. The classification was based solely on climatic variables and their interactions without reference to vegetation or other features.

Powell and MacIver (1975) extended this analysis to all of the forested areas of Alberta, but restricted it to the months of May to September because that was the growing season, and because few data were available for other months in the forests. Climatic regions or groups were derived by minimizing the total variance within groups of factor scores by an iterative procedure called hierarchical profile grouping.

The same methodology was applied to the Hinton-Edson region of west-central Alberta by Powell and MacIver (1976). According to statistical tests, the most significant parameters for defining and characterizing climate in the area were mean daily temperature, total precipitation, frequency of days with a mean temperature greater than -2.2°C from May to September, water deficiency from June to September, elevation, latitude, and longitude. These parameters produced six macroclimate zones in the Hinton-Edson region. While considering their classification scheme successful, the authors cautioned that the groups can vary according to the type of variables selected to characterize the climate, the accuracy of the data, and the representativeness of the climate stations.

This classification scheme was applied to all of the forested areas (Powell and MacIver 1977) and agricultural areas (Powell 1978a) of the Prairie Provinces.

Researchers from the Canadian Climate Centre applied the techniques of principal component analysis (PCA), and Turc's climatic index of agricultural potential, to generate an ecological land classification for Alberta (Williams and Masterton 1983). Their study was designed to determine if existing ecoregions are climatically distinct, and to explore possible techniques of incorporating climate more directly into the ecological land classification process. The results showed that both analysis procedures were very useful. Turc's index showed some bias toward growing-season conditions, while PCA, as applied in this study, tended to overemphasize winter temperatures.

2.2 REGIONAL CLIMATOLOGIES

Longley (1972) described climate as the long-term manifestation of weather in all its forms. The climate of Alberta is controlled by its latitude, distance from the Pacific Ocean, proximity to the Rocky Mountains, and prevailing winds. Alberta (Figure 1) extends from the 49th parallel to the 60th parallel. Consequently, the amount of incident sunlight reaching the province changes significantly over the course of a year. The Rocky Mountains act as a barrier to the moderating influences of Pacific Ocean air masses. Not only are the mild air masses deflected or kept to the west, but cold arctic air masses are free to pass through Alberta in winter. The prevailing winds are from the southwest, west, and northwest. These winds, however, shift as storm centres and high pressure cells migrate across the province. These regional influences result in a continental climate that is subject to extremes in temperature and precipitation. Alberta experiences two major seasons: a long cold winter, and a short cool summer, with fall and spring being shorter transitional seasons. On average, these transitional seasons last only about one month. Longley described in detail, and in non-technical language, the characteristic weather of each season.

A brief overview of Alberta's climate for a farm audience was prepared by Charlton, Janz and Toogood (1976). Descriptive climatologies for southern Alberta, the contiguous mountain parks, the Athabasca oil sands region, and urban areas are discussed in the following sections.

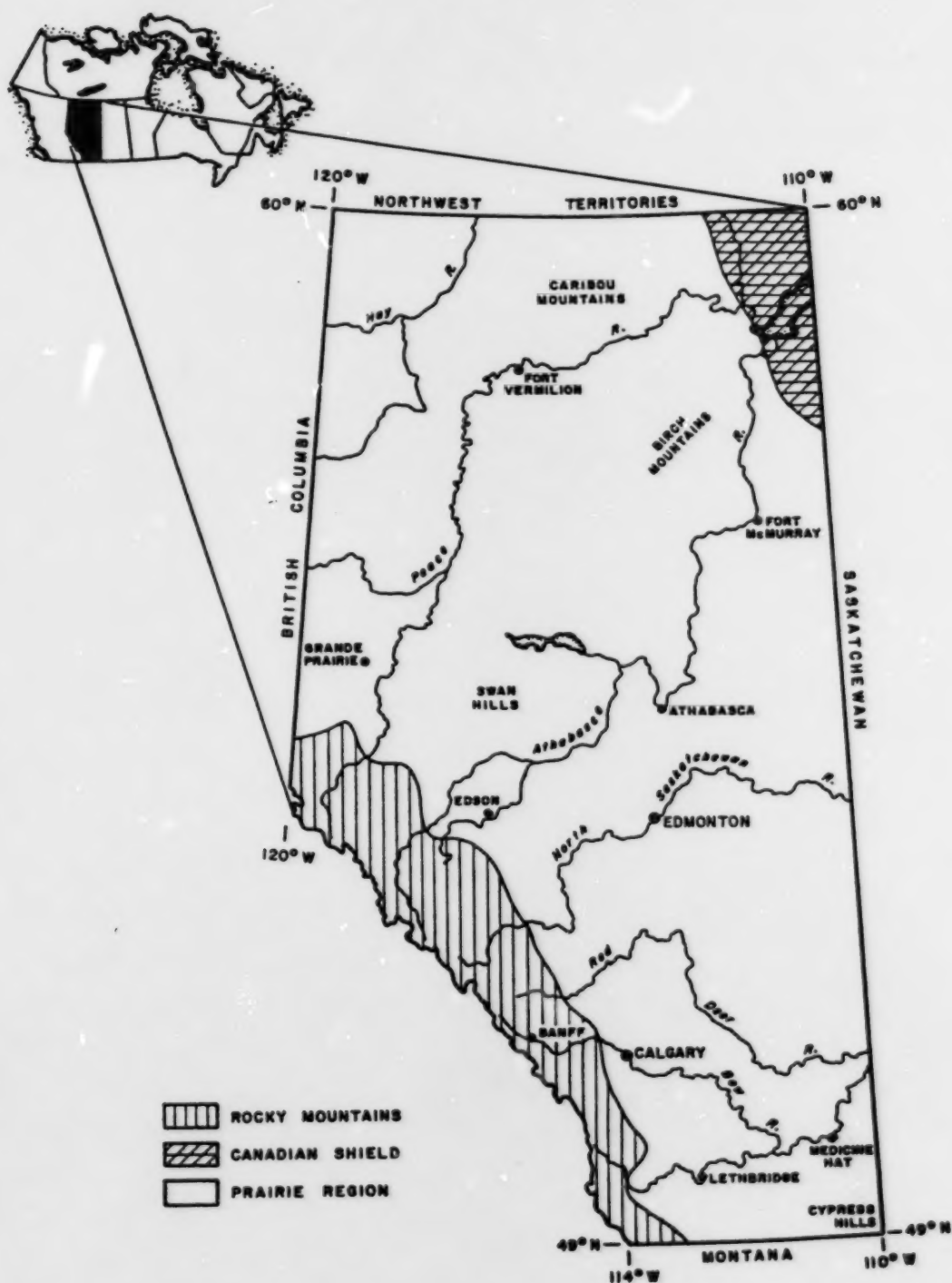


Figure 1. Map of Alberta and its physiographic regions.

2.2.1 Southern Alberta

Over the years, the climate of southern Alberta has received considerable attention. The most comprehensive discussion was prepared before the period 1975 to 1986 by Fletcher (1972). This is a descriptive summary of the weather elements including temperature, sunshine, and precipitation. The means, extremes, and seasonal variations of each parameter are presented. Fletcher described the climate of southern Alberta as having warm summers with occasional hot days, and cool winters that may be moderated by warm chinooks. Precipitation peaked in June and was light in the October-to-March period. The region was moderately windy with winds predominantly from the west or southwest.

Fletcher also discussed climate and agriculture, and urban climates. For high yields, crops in the region must be irrigated from June onward. Average annual water deficits were about 20 cm, except in the Cypress Hills (10 cm), and in the Rocky Mountains (0 cm). With the exception of Calgary, most urban communities in southern Alberta have not had downtown weather stations and, therefore, no quantitative information was available to assess "heat islands" and other effects.

2.2.2 Contiguous Mountain Parks

Mountain climatology is particularly difficult to describe because of the variability caused by slopes and elevation, which overwhelm the influence of latitude, the primary climate control of non-mountainous surfaces. The Climate of the Contiguous Mountain Parks (Janz and Storr 1977) is the definitive work on the Banff and Jasper

National Parks. The authors have combined all available climate data with qualitative observations to produce a remarkably useful and interesting document. They found the parks' climate to be extremely variable on all time scales and surprisingly dry, especially in many of the largest valleys. Above the timberline, the climate was found to be harsh, though few quantitative observations existed. Their discussions of the standard climate variables included many descriptions of special effects caused by the topography. In addition, chapters were devoted to applications of climate data to park management, fire weather and prescribed burning, vegetation, wildlife, siting and care of weather instruments, air quality, hiking and climbing, and avalanches.

One difficulty in describing the climate of a mountainous area is the lack of long-term records in a variety of topographical settings. Long-term data sets can serve as control sets for short-term studies. Janz and Storr strongly recommended that key long-term stations in the parks be continued. They recommended also that the present network of other climate stations, snow courses, and precipitation storage gauges be continued; and that automatic weather stations be installed to give adequate coverage in remote, inaccessible areas.

The second large work dealing with mountain climates was the Climate of Kananaskis by Cote (1984). This study was undertaken to meet the needs of both public and private concerns in terms of assessing Kananaskis' climate for future cultural developments. The area is particularly important for outdoor recreation. The climatic characteristics of the region were described in detail under the topics

of temperature, precipitation, wind, humidity, and extreme events, with special attention to topographic influences. Extensive use was made of data from Marmot Creek Experimental Watershed. The report closed with a brief section on applied climate, which focussed on site selection for recreational activities, air quality, and fire weather.

2.2.3 Athabasca Oil Sands Region

The climate of the Athabasca oil sands region of northeastern Alberta was studied extensively in anticipation of major resource developments in the area. The Alberta Oil Sands Environmental Research Program (AOSERP) started in 1974. Five potential atmospheric environmental problems resulting from resource development in the oil sands were identified (Alberta Environment 1974):

1. ambient ground level concentrations of SO_2 near the source;
2. pollution sinks and acid precipitation on a regional scale;
3. water and ice fogs;
4. odour; and
5. inadvertent weather and climate modification.

The available meteorological and climatological data of the region were inadequate to address these concerns. The report identified the research and data requirements that would be needed to solve the anticipated problems.

Coincident with this work, others studied the local climate within the framework of development of a regional plan for northeastern Alberta (Ekistic Design Consultants Ltd. 1975). A brief synopsis of the

climate of the region, based largely on data from Fort McMurray, Fort Chipewyan, and the Alberta Forest Service was presented. The authors argued that, from a planning perspective, topography was the most important climate control. They divided the region into three topoclimatic zones: the Athabasca Valley zone, slope zones, and upland zones. It was recommended that urban development, and development of intensive recreation areas be encouraged in the slope zones because they offered the best compromise between the favourable and unfavourable climatic characteristics of the valley and upland zones.

In the Climatology of the Alberta Oil Sands Environmental Research Program Study Area (Longley and Janz 1978), long-term climate records from the Fort McMurray, Embarras, and Fort Chipewyan airports were used to give a descriptive overview of the climate. For the purposes of this report, the most critical climate variable was wind because of its central importance in air pollution models. Wind data were sparse, and knowledge of the local topographical influences on wind direction and speed was lacking in 1978. The authors concluded that using wind data from Fort McMurray airport to model wind features was unpromising. More wind information was urgently needed for the oil sands region.

Rudolph et al. (1984) completed a follow-up assessment of the climate of the Athabasca oil sands area, using more recent data. This study incorporated hourly values of precipitation, temperature, relative humidity, and wind from the automated weather stations which began collecting data in 1976. However, the new data sets were disappointing

in terms of data quality, length of acceptable records, and overlapping lengths of records between stations. Data from the Alberta Forest Service lookout sites and Fort McMurray, plus minisonde measurements of temperature and winds aloft, were used to complement the automatic station data. Monthly rainfall varied greatly from station to station, and was not well estimated by measurements at Fort McMurray. Surface winds were strongly controlled by terrain. In fact, terrain-induced airflows predominated in winter and fall, and on spring and summer evenings.

Leggat (1981) included some descriptions of the climate of the Muskeg River-Huckleberry Tower area in his assessment of the suitability of the region for caribou habitat.

2.2.4 Urban Areas

The climates of the two major urban centres in Alberta were described in recent publications of the Atmospheric Environment Service of Environment Canada. Both volumes are part of a series of publications on the climates of Canadian cities.

Following a discussion of the controls that govern Edmonton's climate, Olson (1985) presented statistics and descriptions of mean values and variability of the most important climate variables for each season.

These variables included ice formation on the North Saskatchewan River, and wind chill in winter; frost in summer; and relative humidity in spring and summer. The report ended with discussions of comfort, winter heating, summer cooling, recreation, and gardening.

The Climate of Calgary (Klivokiotis and Thomson 1986) followed much the same format as that used by Olson for Edmonton, but included much more on the climatic influences of chinooks. In addition, information on severe weather was included in the section on winter climate.

2.3 CLIMATE MONITORING

In order to describe and quantify the climate of a particular location or region, careful observations must be made and recorded. A single monitoring station is insufficient to describe the climate of any region because horizontal variations are often large. Climate monitoring networks are needed for at least three reasons: (1) to obtain areal mean values; (2) to interpolate between observing points for correlation with biological variables, or for local climate description; or (3) to use as initial conditions in an empirical or physical prediction model (Munn 1970). The Guide to Climatological Practices (World Meteorological Organization 1960) stated that "Ideally, the number of stations at which any particular climatic element is observed should be large enough to permit a complete analysis to be made, without resorting to doubtful hypotheses, of the geographical distribution of the mean values, frequencies, extremes, and other characteristics of this element."

Powell (1978b) prepared a wide-ranging review of the needs of forestry disciplines for climatic observation networks. He discussed network types, standards, and spatial scales, and he emphasized the difficulties that are encountered in obtaining representative measurements in a forest. He concluded with the hope that future micro- and meso-climate forest networks would be integrated with existing stations or large-scale networks.

The World Meteorological Organization serves as an umbrella agency which formulates standards for climate network research and encourages national meteorological services to adopt these standards (World Meteorological Organization 1960, 1983). In Alberta, a variety of agencies, both in the public and private sectors, have set up weather and climate monitoring stations throughout the province. The parameters monitored depend upon the objectives of the agency involved. Parameters such as temperature, precipitation, solar radiation, humidity, snow cover, and cloud cover, however, are commonly recorded.

The annual meeting of the Alberta Climatological Association in 1978 was devoted to the design, description, and use of climate networks in Alberta (Alberta Climatological Association 1978). The following sections will discuss data management, and the existing federal and provincial networks in Alberta, as described in published reports. Other monitoring and measurement programs are known to be underway, however, published reports on these networks are not available. Kerr and Papirnik (1985) briefly discussed the measurement programs underway at the Universities of Alberta, Calgary, and Lethbridge.

2.3.1 Federal Government Networks

The Atmospheric Environment Service (AES), Western Region of Environment Canada, based in Edmonton, operates a number of networks related to the AES core programs. A climate data network consisting of 265 stations in Alberta and the Northwest Territories is managed by AES. Climate reports are also submitted from an additional 40 stations which comprise the core meteorological network operated jointly by the Atmospheric Environment Service and Transport Canada (Kerr and Papirnik 1985). A number of networks are maintained. These are: (1) temperature; (2) precipitation; (3) supplementary wind; (4) synoptic stations; (5) rate of rainfall; (6) pan evaporation; and (7) sunshine and soil temperature networks. These networks are illustrated in Figure 2. Table 1 is an updated version of Table 1 from The Climate of the Prairie Provinces (Longley 1972).

Fortunately, in Alberta the AES network has been greatly augmented in the forested zones by the Alberta Forest Service network of fire-weather stations. Without this network of 142 stations, data collection in the forested regions of Alberta would be sparse. These data are collected during the months of May through September only, which restricts their use in some applications.

2.3.2 Provincial Government Networks

A major source of information on provincial climate networks was compiled in 1983. The report, An Assessment of Collection and Handling of Climate Data by Alberta Government Agencies (Hansen and Jones 1983),

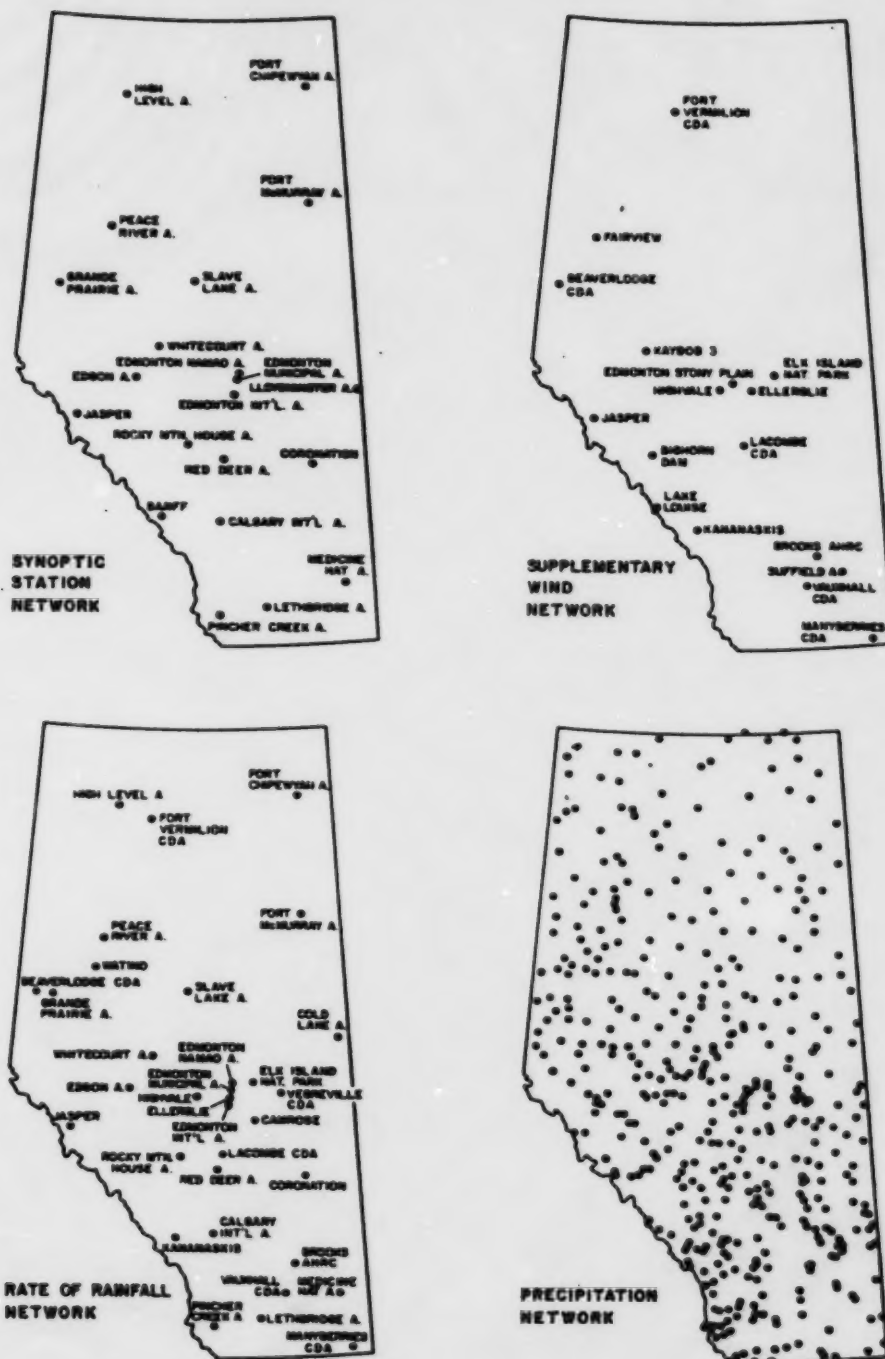


Figure 2. Existing federal government networks in Alberta supplemented by the Alberta Forest Service precipitation and temperature networks.

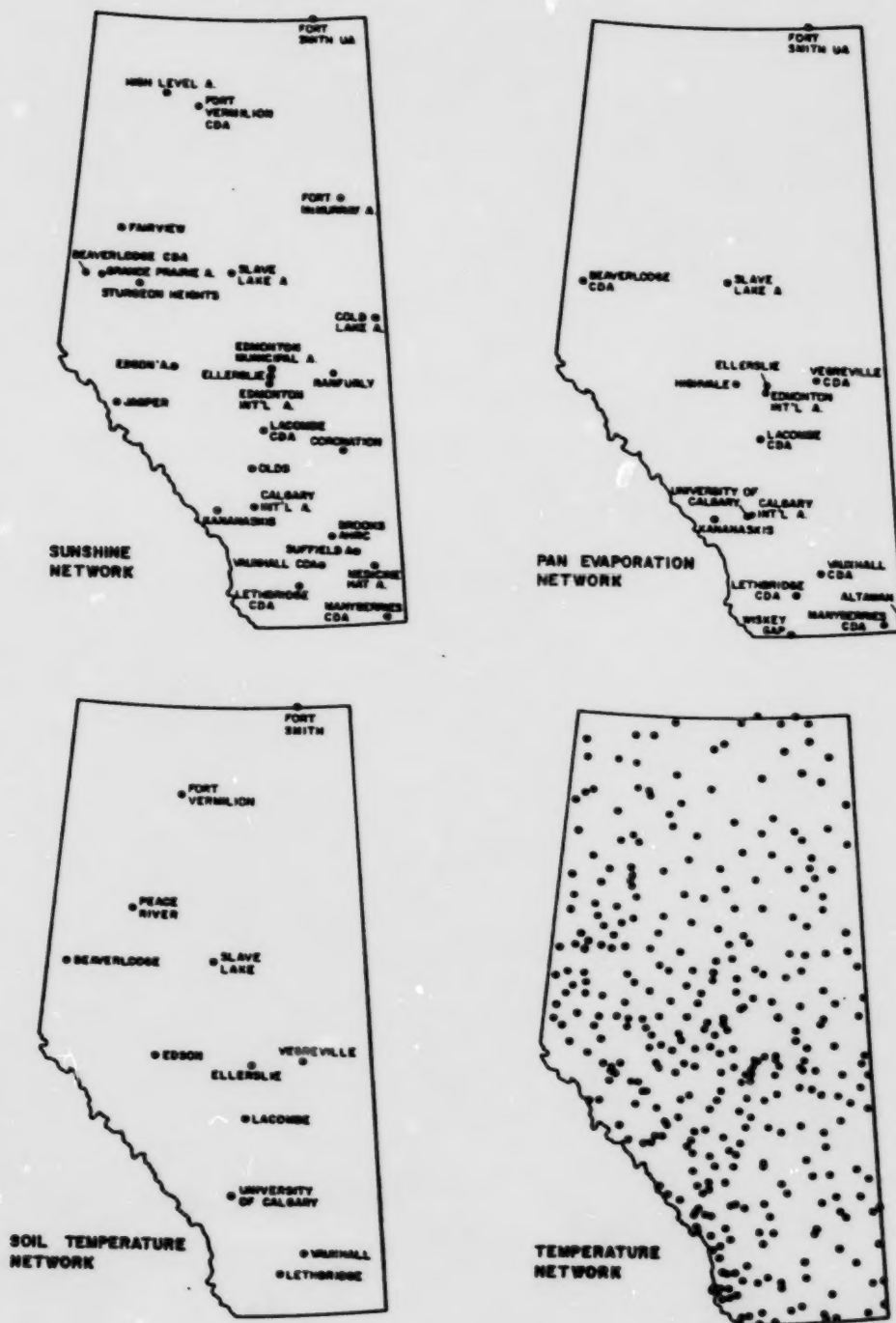


Figure 2. Concluded.

Table 1. Number of climatological stations in Alberta taking records of weather elements in 1987.

Data Observed	Number
Hourly weather	25
Temperature, full year	232
Temperature, summer only	142
Precipitation, full year	284
Precipitation, summer only	142
Rate of rainfall	32
Wind (Supplementary)	14
Soil temperature	10
Evaporation	13
Sunshine	23
Radiation	4
Upper air temperature, humidity and wind	1
Snow survey	14

identified 13 government agencies that collect climate data. The report listed the agencies or government departments, the parameters measured, and a brief description of the purpose for collecting the data. It was noted that Alberta Environment and Alberta Energy and Natural Resources (now Forestry, Lands and Wildlife) were the two departments most heavily involved in climate data collection. Most data collected were used in a historical sense for research projects or case study analyses. Four agencies (Alberta Forest Service Protection Branch, Alberta Environment River Flow Forecast Centre, Alberta Parks Outdoor Recreation and Planning Branch, and the Alberta Research Council) also used climate information on a real-time basis for operational aspects of their work. Although, this report is several years old, it still has valuable information on climate networks and the responsible agencies.

The Alberta Climate Station Catalogue (Alberta Energy and Natural Resources 1985) included a listing of all the locations in the province where climate-related parameters were measured. The parameters were listed but no other explanatory details were given. The catalogue which can be referenced by either agency or map sheet is useful if one wants to identify quickly all measurement sites within a given region.

The Alberta Oil Sands Environmental Research Program (AOSERP) conducted a climate monitoring program in the Athabasca oil sands area from 1975 to the early 1980s, in conjunction with a study of precipitation chemistry. The intent of the program was to quantify the total ionic and particulate loading of the atmosphere as well as to assess the spatial distributions of pollutant deposition resulting from industrial

emission sources in the area. This network extended to a range of 120 km from the Syncrude and Suncor oil sands plants (Davies et al. 1985).

The real-time hydrometeorological network operated by Alberta Environment was described by Coles and Graham (1983). This is a state-of-the-art network incorporating satellite-based data collection platforms, and it allows accurate flood forecasting to be carried out at the Alberta River Forecast Centre.

The subject of network planning was discussed by Meeres (1978). He stressed that, in a time of limited manpower and financial resources, considerable effort must be devoted to network planning to maximize the benefits of the network. Factors to be considered in a climatological network design include known climatological variability, land use, economic factors, topography, and existing networks. Meeres suggested that network design criteria should reflect social and economic needs of the area, the physical relationships between climate and topography and the gradients of important climatological parameters. With these criteria in mind, Meeres developed a sample climatological network design for Alberta.

2.3.3 Data Management

The continuation of climate research in Alberta depends on the availability of high quality data. These data are generated from the established monitoring networks, and therefore good coordination between the data generators and the data users will enhance climatological

research. The wide variety of ways these basic data are used is illustrated by the research and monitoring projects described in the project inventory catalogue in a recent proceedings of the Alberta Climatological Association (Alberta Climatological Association 1986).

The collection, coding, quality control, and archiving of climate data are integral components of the overall climate network management. Carefully archived data make it easier for users to find, access, and use the data. The techniques employed by the provincial government agencies in handling the data range from completely manual to fully automated methods. Hansen and Jones (1983) summarized the data handling methods for each agency. In 1982, most data were stored as hardcopies (i.e., on paper or data sheets) as opposed to storage on tapes or disks. At present, in 1989, there is no central provincial agency to coordinate or store all the data. There is, however, a central data archive for data from the federally-managed AES networks. All AES standard data and Alberta Forest Service weather data are archived in AES headquarters in Downsview, Ontario.

3. PHYSICAL CLIMATOLOGY

The spatial and temporal variations in climatic parameters (e.g., temperature, radiation, humidity, precipitation, and winds) are the results of the interaction of various physical processes involving the transfer of solar and terrestrial radiation, heat, moisture, and momentum within the atmosphere, and between the atmosphere and the earth's surface. These processes are, in turn, influenced by differences in latitude, altitude, topography, juxtaposition of land and water surfaces, and snow and ice cover. Scientific studies dealing with precipitation, lightning, chinooks, tornadoes, and solar radiation in Alberta are summarized in the ensuing sections.

3.1 SOLAR RADIATION

Solar radiation is the fundamental source of energy that contributes to all physical processes occurring in the atmosphere, and supports life on earth. Solar radiation is scattered, absorbed, reflected, and transmitted by the atmosphere before reaching the earth's surface. Once reaching the surface, it is reflected or absorbed. The collection and analysis of solar radiation data are essential for many applications in research and industry. A tabulation and analysis of solar radiation data for Alberta was prepared by Hay (1977). A summary of solar radiation data collection programs and applications in Alberta was presented by Gourlay (1985). Atmospheric factors which affect solar radiation, regional solar radiation activities, and solar energy as an alternative energy source are discussed in the following sections.

3.1.1 Atmospheric Factors Affecting Solar Radiation

The incident solar radiation that reaches the outer atmosphere is reduced through absorption, reflection, and scattering by atmospheric constituents such as aerosols, gas molecules, and clouds. The resultant solar radiation, or insolation, that reaches the earth's surface is dependent upon time of year, and the geographical location of the surface area. A series of studies by Sadler addressed the variation of insolation and the atmospheric extinction coefficient² as measured in Edmonton. These variables were further analyzed to obtain atmospheric turbidity, attenuation, and annual variations of solar energy in spectral bands. Insolation and the extinction coefficient were measured in order to derive a relationship between solar radiation and its interaction with building surfaces (Sadler 1970). The annual variation of insolation at air mass zero (sun directly overhead) reached a maximum in March to May and a minimum in November. The highest extinction coefficient was observed in May to June and a minimum occurred in November to December. Annual variations in the ratio of sky-scattered insolation on a horizontal surface to direct normal insolation followed closely that of the extinction coefficient. This ratio is important for controlling room environment comfort, and for optimizing refrigeration plant capacity.

Sadler (1978a) used measurements of filtered clear-sky, normal-incidence solar radiation to separate that portion of the spectrum not

² The extinction coefficient represents the sum of scattering and absorption.

affected by water vapour from that for which water-vapour absorption and scattering are important. The fraction of normal-incidence insolation influenced by water vapour in the atmosphere was found to be about 60 percent at 60 degrees sun altitude, 67 percent at 20 degrees altitude, and 80 percent at 5 degrees altitude. Maximum energy in this band occurred in March, when the precipitable water, as measured by the Edmonton-area radiosonde data, was low. Minima occurred in July, when precipitable water was at its maximum, and in winter, when the solar elevation angle was low.

Another factor often mentioned in the analysis of insolation is the turbidity of the atmosphere. Turbidity is the total aerosol optical depth of the atmosphere in the vertical, and it is often used as a crude index of dust loading. It varies with season and location. Sadler (1978b) used filtered clear-sky, normal-incidence solar radiation data to study atmospheric attenuation in seven spectral bands. He reported the monthly mean values for each, and computed turbidity factors from the filtered data for comparison with sun photometer measurements, and with turbidity deduced from total or unfiltered normal-incidence insolation measurements. Sadler (1981) presented a comprehensive set of tables and figures that illustrated annual and diurnal variations in irradiance at zero air mass, and extinction coefficients for each of eight spectral bands.

Sadler's research was guided by the Handbook of Fundamentals of the American Society of Heating, Refrigerating and Air Conditioning Engineers (1977), and provides us with an excellent example of the

methodology needed to adapt the measurement and analysis of climate variables to the requirements of specific users.

3.1.2 Regional Solar Radiation Studies

The geographical characteristics of a specific location are important factors in determining insolation variations. In mountainous regions, slope and shading have significant effects on the amount of solar radiation received. The existing solar radiation network of stations in the mountains of Alberta and British Columbia is much too sparse to describe adequately the variations in solar radiation (Hay and Suckling 1978). Numerical models have been developed in attempts to solve the problem. However, these models add little to the spatial coverage unless relatively low accuracy of estimates is acceptable. Hay and Suckling reported a 15 percent error within 15 km of measured solar radiation values, and a 75 percent error within 180 km of measured values. Seasonal variations of extrapolation errors were also noted, and mesoscale variability was difficult to model.

Munro (1975) presented all components of the energy balance for Peyto Glacier, Alberta on one clear day in summer. This glacier had a low albedo of 0.25, which allowed the absorption of large amounts of solar radiation. He found that the ice surface received both sensible and latent heat at all hours and, therefore, underwent ablation at all hours despite net radiative loss at night. An eight-year observation record was used by Young (1977) to establish linkages between mass-balance parameters of Peyto Glacier and nearby climatic data. While

short for such studies, the eight-year record included the largest and smallest winter accumulations of the past 40 years. Net annual mass balance was found to be controlled primarily by the depth of the winter snowpack, and by the summer temperature record.

Nkemdirim (1978) found that surface cooling rates were twice as large over snow as over grass under clear skies. He attributed this result to the larger radiative emissivity of snow, and to the reduced mechanical turbulence over a smooth snow surface.

3.1.3 Solar Energy Applications

The possibilities of utilizing solar energy as a viable alternative to conventional energy sources has been explored to some extent in Alberta. Rachuk (1977) pointed out that, of 50 stations measuring global solar radiation in Canada, only 3 were located in Alberta at the time of his study. He identified a need for simultaneous measurements of direct, and total solar radiation; temperature and winds; and durations of solar radiation below certain threshold values for useful applications of solar energy in the province.

Some of the potential for solar and wind renewable energy use in Alberta was quantified by the large, eight-year Solar and Wind Energy Research Program (SWERP), carried out by the Alberta Research Council (1986). High-quality instruments were installed at Fort McMurray, Edson, Ellerslie, Rocky Mountain House, Coronation, Pincher Creek, and Lethbridge. Radiation measurements included global, diffuse, earth's-surface reflected, net, and solar radiation impinging on vertical

surfaces in the four cardinal directions. Unfortunately, persistent problems with the data acquisition system resulted in significant data loss. Consequently, it was not possible to derive confidence limits for extrapolation of available solar energy to other locations in the province. SWERP wind speed measurements appeared to be incorrect on the basis of comparisons with Atmospheric Environment Service data. Nevertheless, numerous data summary tables and figures, including much unique data were prepared, and the potential exists for future exploitation of the data.

Gilpin (1977) reported on the use of south-facing windows to provide partial heating for an Edmonton household. A dynamic model of building response to time variations in radiation fluxes, and air temperatures; and climatological solar radiation data, were used to make recommendations for the design of a house which would utilize solar energy efficiently. Improved performance resulted when thermal mass walls were installed, south-facing windows were equipped with overhangs, and use was made of automatic thermal shutters.

Ahmadi and Glockner (1984) used a dynamic energy-balance model for several layers of soil and air to simulate the effects of variable cloudiness on the operation of a greenhouse in southern Alberta. Changes in greenhouse climate due to changes from a partly-cloudy day to an overcast day were not significant. However, unacceptable vegetation temperatures occurred on clear days, and it was necessary to reduce the external solar heating.

3.2 PRECIPITATION

3.2.1 Precipitation Climatologies

Descriptive precipitation climatologies have been published for Alberta by Longley (1972) and Laycock (1978). Nkemdirim and Weber (1976) used long-term historical precipitation records to derive the parameters of gamma distributions of the precipitation regime in the province. They established three broad precipitation regions: (1) the mountain region which had the highest precipitation amounts; (2) the central region, or "Alberta storm-track region", which had the best consistency of rainfall; and (3) the dry belt which had high variability with low annual amounts. The lack of province-wide wet or dry spells suggested that precipitation in Alberta was controlled largely by air mass movements and frontal passages, according to the authors.

Powell (1977) attempted to derive a precipitation climatology for the mountain and foothills areas of Alberta by analyzing data from the Alberta Forest Service, Eastern Rockies Forest Conservation Board, and Atmospheric Environment Service observation stations. Mountain rainfall ranged from less than 300 mm in the Jasper area, and in the Oldman River and Bow River corridors, to more than 500 mm in the western Waterton Lakes region. Most precipitation fell as rain in the eastern foothills, but snowfall was dominant at higher elevations. At Lake Louise, only 37 percent of the total precipitation fell as rain. Areas south of Jasper-Hinton and Nordegg-Rimbey recorded the highest precipitation in December. In the extreme southwest, the months of lowest precipitation

amounts (July and August) followed the month of highest precipitation (June). Spatial and temporal distributions of rainfall in the mountains were difficult to establish with confidence, however, because of the sparse station network and the high variability of the precipitation. Powell recommended that short-term meteorological networks be incorporated into the database so that a more accurate precipitation climatology can be achieved in the future.

3.2.2 Orographic Precipitation

One of the important physical processes which results in precipitation is orographic lifting in which an air mass, or parcel of air, is forced to rise over a topographic barrier. Reinelt (1970) found that winter orographic precipitation depended on distance from the Rocky Mountains, and he noted a maximum of orographic precipitation just east of the Continental Divide. Summer precipitation had a large convective component, and was not necessarily dependent on distance from the mountains. Reinelt estimated that orographic uplift contributed 37 percent to the total mountain rainfall. This contribution decreased to 13 percent in the plains where convective processes dominated.

Barlow et al. (1986) described a preliminary climatology of the microphysical characteristics of orographic clouds. Measurements from 11 instrumented aircraft flights through orographic clouds in two field seasons showed that the ratio of cloud liquid water to ice crystal concentration was high. This ratio increased with cloud temperature, which implied that the precipitation-forming process was less efficient

at higher temperatures because of lack of condensation nuclei in the form of ice crystals. In other words, orographic clouds contained large amounts of liquid water which could be transformed into precipitation if some of the cloud droplets could be stimulated to grow. The geographical distribution of cloud liquid water content indicated that orographic cloud formation was most common west of the Continental Divide, with maximum liquid water content, or higher precipitation potential, upwind of the highest mountain ranges.

3.2.3 Convective Precipitation

Convective precipitation results from the buoyant rise of moist unstable air. Convective precipitation was studied by the Alberta Research Council in their assessment of the utility of weather radar data to describe space and time variations in rainfall. Data collected since 1975 were used to derive rainfall intensity-duration curves within a radius of 150 km from the radar at Red Deer, Alberta. The basic formula for rainfall rate is the "Z-R relationship", where Z is radar reflectivity and R is rainfall rate. An empirical Z-R relationship, developed by Wojtiw (1986a) from Alberta data, gave good agreement with observations. Perhaps the most important application of this technology is in the hydrological field of flood forecasting. Barge and Humphries (1977) emphasized that radar gives much more higher resolution of rainfall amounts than conventional observations. Other possible applications of radar technology include severe weather warnings, farm management, water management, construction, irrigation, weather modification, reservoir and dam management, and analysis of trends in precipitation patterns.

The realization of latent and potential instability of the atmosphere by orographic lift is a major precipitation-forming process in the Alberta Rocky Mountains. Because of large variations in the orientation and location of major mountain barriers, precipitation triggered by orographic lift can be highly variable within small geographical areas. Janz (1977) assessed the contributions of convective and orographic precipitation in the mountain parks by looking at the characteristics of wet and dry areas in the Banff and Jasper regions. The dry stations were located generally on flat plains inside the eastern-most mountain barrier with mountains to the east and west. Storage-gauge data were used to derive precipitation-elevation regression equations. At some unknown but high elevation above 2300 m, it was expected that these equations would fail, and that precipitation would begin to decrease with height.

When extreme levels of atmospheric instability are present, as occurs with a cold low-pressure centre aloft, then the probability of a severe rainfall event is at a maximum. The climatology of severe rainfall events, generally of duration 72 hours or less, was studied by Verschuren and Wojtiw (1980), and Wojtiw and Verschuren (1981), for the years 1921 to 1978. The average occurrence of rainfall amounts greater than 50 mm was 11 per year, with most of these in June and July. The highest frequency of extreme rainfall amounts was in the Waterton Lakes area. In that area, amounts greater than 50 mm occurred twice per year on average, and amounts greater than 150 mm occurred once in 10 years. The four preferred areas of severe rainfalls in Alberta were: (1) south

of Calgary; (2) from Edson to Edmonton; (3) from Lesser Slave Lake to Fort McMurray; and (4) the Fort Chipewyan region. The highest frequency of severe rainfall events was in June in southern Alberta, and in July in central Alberta.

Climatological data, coupled with the results of studies of severe rainfalls such as those described above, were used to compute probable maximum precipitation (PMP), and probable maximum flood (PMF) for the Battle River near Gwynne, Alberta (Figliuzzi 1982). In brief, PMP was computed by maximization and transposition of the largest nearby historical rainstorms, and PMF was computed from estimations of runoff volumes and hydrograph shapes. The results, for the Battle River near Gwynne, were 33.5 cm (48-hour), and $589 \text{ m}^3\text{s}^{-1}$, respectively.

3.2.4 Snow

Snow climatology research in Alberta has been limited mostly to the southwestern portion of the province. In 1982, the Alberta Research Council initiated a study of snow in the southern Alberta Rocky Mountains for the purposes of assessing the potential for augmenting snowfall by cloud seeding. Barlow et al. (1983) investigated snow climatology from a seasonal and geographical perspective using records that ranged in length from 9 to 30 years from a variety of snow measurement networks. Maximum annual snowfall was found at the highest elevations with much smaller amounts east and west of the Continental Divide, and in the Columbia River valley. Monthly snowfall amounts peaked in January, and the average snowpack water equivalent peaked in early May. Equations for both, as functions of elevations, were derived.

Mid-winter snowfalls were found to be most frequent west of the Continental Divide, while spring snowfalls were most frequent east of the Divide. Only weak relationships were found between snowfall and upper-air parameters such as vorticity, upper-level winds, 500 mb and 700 mb temperatures, vertical temperature gradients, humidity, and the heights of 500 mb and 700 mb constant-pressure surfaces.

It is apparent from the preceding studies that topography is an extremely important factor in the assessment of snow climatology over mountainous terrain. Other factors that may also affect snowfall are cloud microphysical variables such as cloud-base temperature, cloud liquid water content, and cloud ice crystal concentration.

3.2.5 Hail

Alberta, especially central Alberta, has one of the highest frequencies of hail in the world. In recent years, crop losses have totalled over 100 million dollars per year (Wojtiw 1986b). Makowsky (1982) reported 98 million dollars property damage and 3.1 million dollars crop damage caused by one evening of intense hail in and around Calgary. Because of the devastating economic dent caused by hail, Alberta has been the location of some of the most extensive hail research anywhere. Most of this research effort was undertaken by the Alberta Research Council (ARC) with funding from the Alberta government. This research has focussed on both the climatology of hailstorms and the application of climatology to improved understanding of the physical and microphysical characteristics of hailstorm development. Extensive

research information has become available on artificial cloud seeding from ARC's work. Hailstorm characteristics, and the spatial and temporal variations of hailfall have been examined extensively by Wojtiw (1975, 1977, 1979, 1981, 1986b). Haildays per year, daily onset times, durations, hailswath dimensions, areal coverage, areal frequency of occurrence, point measurements of hail intensity, point measurements of hail kinetic energy, and hail size have all been studied, especially in relation to crop damage.

3.2.5.1 Temporal variation of hailfall. A hailday is a day on which hail fell somewhere within the Alberta Hail Project area, which was delimited by a radius of 128 km to the east and west of the radar at Red Deer airport, and by townships 25 and 48 to the south and north, respectively. The frequency of haildays was greatest in June and July, with a maximum of 90 percent on July 5, based on 29 years of observation. There was an average of 60 haildays per season. Large hail (larger than walnut size) was present on 39 percent of all haildays. The frequency of large hail increased from 10 percent in May to 40 percent in late July. Crop damage from hail was most common between mid-July and the end of August. The single worst hailday in a given year caused 20 percent of the total annual crop damage, and the four worst haildays caused 50 percent of the total crop damage.

Hailfall showed a peak frequency of onset times in late afternoon (1600 to 1800 local time), which corresponded with the time of maximum surface temperatures. The duration of hailstorms was expressed in terms of the time periods of continuous hailfall at one point. Half of all

storms lasted less than 5 minutes at one point, while only 1 percent lasted more than 30 minutes at one point.

3.2.5.2 Spatial variation of hailfall. The areal extent of the hailfall was determined by measuring the length and width of the path impacted by the hail, or the dimensions of the "hailswath". Most hailswaths (77%) were less than 6 km in width, 90% were less than 30 km in length, and 74% were less than 30 km² in area. A major hailswath was defined in terms of the number of hail reports, and the size of the largest reported hail. There was an average of 27 major hailswaths per year, with approximately half occurring in July. The largest frequencies of occurrence of hailswaths was in the Rocky Mountain House area, eastward through Gull Lake, and from Sundre to Bowden.

3.2.5.3 Intensity of hailfall. Crop damage from hail is a complex function of hail properties, wind, crop type, and crop growth stage (Strong and Lozowski 1977). Wojtiw (1979) reviewed research in Alberta on hailpad measurements and crop damage factors. A hailpad is a flat horizontal styrofoam pad upon which hailstones leave imprints that depend on stone size and speed. From an assessment of hailpad indentations it was possible to infer impact energy density (Jm⁻²) which was then related to some measure of crop damage. The results confirmed the expectation that crop damage increased with impact energy density, and showed that the rate of increase varied with stages of crop development.

3.2.5.4 Climatology of hailstorms. In a climatological comparison of hailstorms in Switzerland, Canada, and South Africa, Admirat et al. (1985) discussed the similarities and differences in the frequency of hailstorms, and the synoptic factors involved in the development of the storms. The majority (70 to 90 percent) of all hailstorms in the three countries originated from convective instability as isolated or scattered air mass storms, while the most severe storms were associated with cold fronts. Parameters such as lifetime, maximum storm height, dimension, number of storms, maximum hail diameter, impact kinetic energy, and hailswath surface area were similar in Alberta and South Africa, and were generally much less in Switzerland storms. In general, hailfall was pulsating, not steady (i.e., the intensity of hailfall within a hailswath was not constant). Differences between hailstorms from country to country were dependent on orographic, synoptic, thermodynamic, and convective factors, and not on cloud microphysical processes.

3.3 Chinooks

Chinook is an Indian word meaning "snoweater". A chinook is difficult to define precisely, and as a result many definitions have been proposed. Most definitions are descriptive and refer to the temperature and wind characteristics of the phenomenon. For example, it has been called "a warm, dry, gusty wind from the mountains accompanied by rapid temperature changes" (Lester 1975). Because a chinook is a spectacular event with important consequences for agriculture, hydrology, and local climatology, it has received much attention from the research community.

3.3.1 Physical Description

Most published studies of the chinook have been descriptive in nature (Lester 1975, 1976a, 1978; Mathews and Hicks 1979b; Mathews et al. 1984). Lester (1975) stated that one conceptual model of the chinook includes a large-scale advective component, and a mesoscale wave component. He argued that the mesoscale waves have wavelengths of the order of 100 km, which are much larger than ordinary mountain lee waves, or Scorer waves. Measurements in Alberta, in support of this concept, were described by Lester and McPherson (1977).

The vertical structure of the chinook, and its rapid changes with time, are difficult to measure by traditional methods. Measurements with airborne sensors, and satellite imagery, have been used to identify characteristic chinook features (Lester 1976b; Lester and McPherson 1977). Mathews and Hicks (1979b) used a monostatic acoustic sounder in Calgary to probe the turbulence structure of the lowest kilometer of the atmosphere during a chinook. The sounder recorded descending multiple layers, followed by a deep layer (200 to 500 m) of ground-based turbulence with a diffuse and variable upper boundary. The descending layers exhibited wave-like motions. The authors concluded that temperature and wind profiles, measured nearby, were necessary for accurate interpretation of the acoustic sounder data.

In a subsequent study, wind and echo-layer data from Doppler and monostatic sodars at three sites in Calgary were analyzed for four cases of Arctic frontal passages (Mathews et al. 1984). All showed variations in the onset of winter chinooks. The new Doppler technology revealed many small scale features that had not been studied previously.

3.3.2 Chinook Forecasting

Accurate forecasts of the onset and duration of a chinook can be beneficial with respect to air quality trends, street maintenance, snow removal, and general physiological well-being, according to Drews (1981), who discussed forecasting techniques. The 700 mb (3000 m) patterns of winds and temperatures were found to be closely related to strong chinook occurrences in southwestern Alberta. Forecasts can be achieved by manual extrapolation and modification of observed west coast 700 mb patterns, or by use of numerical predictions of such patterns. Other useful aids were control-line charts, track maps of cold surface anticyclones across the plains, and objectively-determined weather map types.

3.3.3 Chinooks and Air Pollution

Two studies were initiated in the late 1970s to investigate the effect of chinooks on air pollution levels in Calgary. A preliminary study of the influence of mountain-generated wind systems on Calgary's air quality concluded that chinooks by themselves were not a factor in causing poor air quality (Western Research and Development Ltd. 1977). There was some indication that poor air quality had a tendency to occur during relatively calm periods preceding and following a chinook. Since chinooks do not occur and dissipate on a diurnal basis, another explanation was needed to account for the observed poor evening air quality. The authors recommended further study into the conditions favouring poor air quality days in Calgary.

Nkemdirim and Leggat (1978) averaged downtown air pollution indices in Calgary and found them to be many times higher on chinook days than on non-chinook days. The differences were attributed to low mixing depths on chinook days, and to poor ventilation caused by wind sheltering of the downtown core. In addition, the authors stated that "a chinook period is marked by strong advection of pollutants from industrial sources to the (downtown) area". Because the industrial sources in Calgary were located mostly to the southeast of the city centre, this statement implies that days with low-level winds from the southeast were included as chinook events in contrast to the usual expectation of westerly surface winds. The extent to which pre-chinook conditions and "upper air chinooks" were included as chinook days is not clear from the paper.

3.4 LIGHTNING

Lightning strikes are major causes of forest fires in Alberta and, therefore, the climatology of lightning is of interest to the forest industry. A lightning-detection system, consisting of seven directional finders, a central position analyzer, and a remote display processor was set up in the province by the Alberta Forest Service. The purposes of this network were to assess the climatology of lightning, and to provide real-time lightning strike data for operational use. Nimchuk and Janz (1983) reported that two types of lightning were common in Alberta. These were: (1) positive lightning, where negative charges are transferred from the ground to the cloud base; (2) negative lightning

with the reverse transfer. The cloud-to-ground potential-gradient threshold is greatest for positive lightning. Therefore, the electric current lasts longer and is more nearly continuous with positive lightning, and fuel ignition is more likely. Positive lightning is more common in mid and northern latitudes because of the lower cloud temperatures. In Alberta, positive lightning was common especially in cool fall weather. Many of the dry lightning strikes in northern Alberta were thought to be positive.

Loss of human life from lightning in Alberta has averaged one to two persons per year in recent years, much below the annual averages for the 1920s and 1930s.

3.5 WIND

Most wind research in Alberta was undertaken in relation to pollutant dispersion, energy, erosion, and regional climatologies, and has been described in other sections of this report. An exception was Thyer (1981) who investigated the diurnal variations of summertime low- and mid-level winds (900 to 6000 m) over the cities of Edmonton and Calgary. Observed diurnal variations in vertical wind shear were consistent with the hypothesis of a thermally-driven wind system that resulted from daytime heating and nighttime cooling of the slopes of the Rocky Mountains. No correlation was found between this wind system and hailstorms in southern Alberta.

3.5.1 Tornadoes and Other Severe Weather Events

Perhaps the most devastating severe weather phenomenon is the tornado. A climatological study of past tornadoes in Alberta, based on archived weekly newspapers and community histories was reported by Hage (1977, 1984). A portion of the list of tornadoes obtained in these studies was used also by Newark (1984) in his report on tornadoes in Canada.

Tornadoes in Alberta have been reported as early as March, and as late as November, but 90 percent of all strong tornadoes occurred between 01 June and 15 August. A frequency maximum was found in a band extending from west of Medicine Hat to near Edmonton, more or less parallel with the Rocky Mountains. The frequencies of reports of weak tornadoes has increased markedly in recent years, but no evidence could be found of recent trends in the frequencies of strong tornadoes.

The same sources of data were used to identify past occurrences in Alberta of severe weather events such as droughts, wet years, dust storms, summer killing frosts, heavy snowfalls, blizzards, severe winters, ice storms, and non-tornado destructive wind storms. Reports of droughts and severe winters, written by the rural residents who experienced their impact, were analyzed statistically and correlated with long-term climatological data to derive a drought index for southern Alberta, and a severe winter index for central Alberta (Hage 1985). According to these indexes, the three most severe droughts in southern Alberta occurred in 1910, 1919, and 1988; and the three most severe winters in central Alberta occurred in 1906-1907, 1919-1920, and 1935-1936.

4. APPLIED CLIMATOLOGY IN ALBERTA

Climate can have tremendous environmental and socio-economic impacts. However, few impact studies have been carried out for Alberta. Decision-makers are hindered in their consideration of climatic variables because they lack detailed cost-benefit analyses in a number of economic sectors. It is essential to know not only the primary response of the natural system but also the interactive relationships between climatic variables and socio-economic activities. Applied climatological research in Alberta has focussed primarily on agriculture, forestry, water resources, and urban climatology and air pollution. Minimal research has been undertaken in tourism and recreation.

4.1 AGRICULTURE

Climate acts as a major control on Alberta's agricultural industry determining, for example, what crops can be grown and where. The effects of climate on crops are further magnified when stresses such as drought or frost damage render the crops more susceptible to disease or damage by competing organisms.

In Alberta, it is important that all arable land be used to its fullest potential. However, as Alberta exists at the margin of productive agricultural land, the agricultural sector is quite sensitive to climatic variability and change. Measures can be taken to adapt agricultural practices to a variable climate. New strains of crops, such as early-maturing wheat or drought-resistant forage, are being developed. Irrigation schemes, greenhouses, or windbreaks are attempts to grow products locally, and to ameliorate the climate.

Good climate information, in an appropriate form, will assist in decision-making for agricultural activities such as seeding, spraying, and harvesting.

4.1.1 Agroclimatic Capability

Considerable attention has been focussed on assessing land capability for agriculture in Alberta. A major working document (Alberta Soils Advisory Committee 1986) described a system for the classification of arable land for agriculture. The system was based on land and environmental factors, including climate, that affect agriculture. The two principle climate factors were (a) an energy factor which included season length, day length, degree-days, and diurnal temperature range; and (b) a moisture factor which included monthly precipitation, and potential evapotranspiration. These factors, in turn, were modified by spring moisture, fall moisture, hail, and fall frost.

The agricultural potential of the Peace River region has been under study for a number of years (Dupuis 1982, 1983). A climate inventory project was initiated in 1977, and this included the installation of two new dense short-term (3 to 5 years) climate networks. Short-period data were adjusted to reflect 30-year normals by stratified regression analysis. Preliminary results were presented for three basic components for agricultural capability: frost-free period/effective growing period, growing-degree days/photo period, and moisture deficit/moisture budget.

Bailey (1981) discussed the possibilities and limitations of the climate resources for agriculture in northwestern Canada, including the Peace River region. The thermal regime and the seasonality of precipitation is also crucial to crop production. Precipitation during the growing season can be highly variable from year to year. High precipitation during harvest has often lowered crop yields and quality in the Peace River region. The author concluded that agronomic technology will determine the success of agriculture in this region.

The agricultural climate of the Lethbridge area was discussed by Hobbs (1977). The author used an historical perspective to describe the climate, citing early meteorological records dating back to 1902. The basic climate parameters of temperature, precipitation, sunshine, wind, evaporation, relative humidity, and soil temperature for the period 1902 to 1976 were summarized.

A basic constraint to agriculture in Alberta is the length of the frost-free period. A frost-free period of approximately 90 days is required for most cereal crops. Longley (1967) showed that frost-free periods from 1951 to 1964 were significantly longer than those prior to 1950, and he attributed these increases to a rise in minimum temperatures in the spring and fall. Local effects of topography, bodies of water, and climate variability reduced the reliability of frost-free periods calculated from available observations. Longley cautioned that such data should be used only as a guide when making agricultural decisions.

Air temperature data, processed separately for day and night, were used to prepare maps of mean Corn Heat Units (CHU), and probabi-

lities of CHU greater than 2100, for western Canada by Major (1977). The value of CHU = 2100 is considered a minimum for corn as fodder. The probability of CHU > 2100 exceeded 50 percent in more than half of the arable land of Alberta.

4.1.2 Climate Variability and Agriculture

A major hazard to the agricultural industry in Alberta is the variability of the climate. Farmers have to contend with short frost-free seasons, low or excessive soil moisture, adverse growing conditions, and inclement seeding and harvesting weather. The history of climate variability in relation to wheat farming in the Prairie Provinces was reviewed by Treidl (1978). An important conclusion was that the variability of mean annual temperatures and annual total precipitation has decreased since the turn of the century. Mean monthly temperatures exhibited the greatest variability in winter, and the least at the beginning of the growing season. Treidl argued that, with superior grain hybrids, better soil moisture management practices, and political arrangements to stabilize farm incomes, today's prairie farmers are better equipped to deal with drought emergencies than the farmers of the past.

Drought, nevertheless, is a critical problem in Alberta in spite of technological advances. The impact of drought on the agricultural economy is compounded by land use practices, market conditions, pests, diseases, fire, political factors, and recent changes in technology. Findlay (1981) gave an Alberta perspective on drought. He recommended

that careful attention be given to the regional timing and geographical extent of drought in order to bring sense to patterns and sequences of historical droughts. He suggested that climatologists must work with economists to document the effects of drought on water supplies, crops, livestock, hydro-electric power, and the development of social policy. He went on to argue that we need strategies that are based on reasonable historical cases in order to be better prepared for the inevitable droughts of the future.

Grace (1986) found dramatic effects of recent Alberta weather on agriculture. These included droughts, crop failures, grasshopper infestations, wet harvest conditions, and soil erosion. He used data from various sources to illustrate the interactions between climate-related variables and agriculture. Drought involves below-average precipitation, but other factors, such as evapotranspiration, and soil water storage, are also important. Grace and Bailey (1981) stressed the importance of the timing of rain events. Soil moisture is the key. If soil moisture reserves exist, adequate crops can result even in the absence of fresh rainfall.

Grace noted that severe grasshopper outbreaks were recorded in June, July, and August of 1984 and 1985. The climatic conditions that resulted in drought and crop losses were favourable for these pests. Sunny, dry conditions in August, 1983 provided excellent conditions for breeding and egg laying. Mild winter temperatures resulted in nearly 90 percent over-winter survival rates. Direct crop losses attributed to grasshoppers were estimated to exceed \$100 million in Alberta and Saskatchewan in 1984 and 1985.

4.1.3 Wind Erosion

High wind speeds and the resultant soil erosion are serious problems in some agricultural areas of the province. Toogood (1978) called for more wind measurements in the area east of Highway 2 and south of Highway 12, for soil conservation extension work, and research purposes. Soil erosion occurs here each year, but little has been done to correct the problem.

The erosive capability of the wind was described by Gietz (1983). The potential erosion, in tonnes per hectare per year, is a function of soil properties, field length, vegetative cover, a climate factor involving the cube of the wind speed, and a measure of the moisture content of the soil. Gietz mapped the wind factor, and found moderate values over most of southeastern Alberta, and in an area northeast of Edmonton (Figure 3). Conventional wind roses were shown to be inadequate for optimum placement of shelterbelts, and the orientation of strip cropping, soil ridging, and cultivation because of the dependence of erosion on the cube of the wind speed.

4.1.4 Crop Yield

A primary question facing agriculturalists is how to maximize yields. It is recognized that environmental factors, including climate, play a significant role in the response of crops to applied nutrients .

Peters (1977) related yields of wheat, oats, and barley in Alberta to soils data, management practices, and a simple agroclimatic classification, based only on long-term precipitation, and frost-free period data. His results showed significant climate-dependent yield

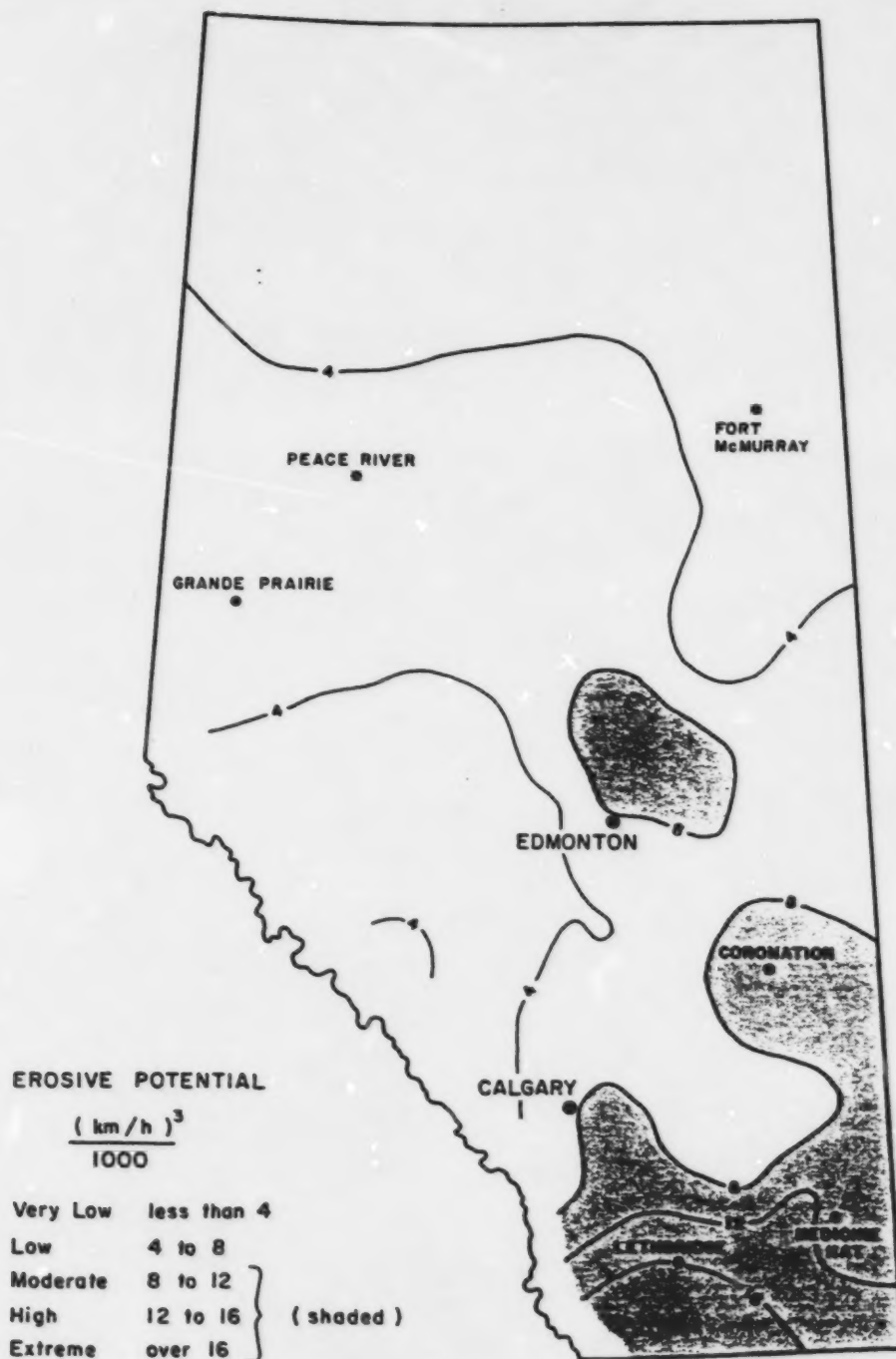


Figure 3. Erosive potential of wind in Alberta.
Source: Gietz (1983)

variations, and clearly demonstrated the need for re-evaluation and refinement of agroclimatic subregion boundaries. A major step in this direction has been accomplished (see Section 4.1.1, Alberta Soils Advisory Committee 1986).

Webster (1977) reported on the influence of fertilizers, soil nutrients, soil order, and weather on barley and forage yields in central Alberta. The "weather" term for barley included climatological data, soil moisture measurements, and growth characteristics of the plant. When this "weather" term was included, 55 percent of crop yield variance was explained. Only 30 percent of forage yield variations were explained by regression on the same soil and nutrient variables, but with a simpler weather term, that included only soil moisture in spring, and rainfall to the first cut.

Further research on the relationship of climatological parameters and barley yields was conducted by Marantz, Kryzanowski, and Cannon (1986). The need to include climatological variables in models for nitrogen fertilizer requirements was recognized. The most significant climatic factors were found to be soil moisture, growing-season precipitation, and evapotranspiration. The investigation showed that barley yields were influenced significantly by fertilizer nitrogen, soil nitrogen, and available moisture. Models with climatic variables helped to explain yearly and site-to-site variations in yields.

4.2 FORESTRY

Alberta is dominated by the boreal forest which can be subdivided into three subregions: the forest-grassland transition region; the predominantly forest subregion; and the forest-tundra transition region (see Figure 4, Singh and Powell 1986). One of the primary sectors of Alberta's economy, the forestry industry generates millions of dollars of revenue and employs many people. Current interest in the use of forest products, the use of forest waste for energy supplements and animal fodder, and traditional forest projects, demonstrates the need for increased forest-climate insights. Inventories of climate-related data and an understanding of climate principles are basic to successful forest management. A forest must be viewed as an ecological system upon which climate acts, directly and indirectly, as a controlling agent. Climate information is required for management decisions about forest reproduction and growth, and for strategies to mitigate the effects of drought, water excess, blowdown, fire, and injury by air pollution, insects and disease (Canada, Environment 1982a).

4.2.1 Climatic Factors in Forestry

The spatial and temporal origins of Alberta forests, their growth rates, species composition, longevity, and total accumulated biomass reflect past and present climatic conditions. The most important dependent variable in forestry is biomass accumulation. Peterson et al. (1983) compiled a comprehensive annotated bibliography and synthesis of known relationships between climatic factors and net primary



Figure 4. Boreal forest of western Canada showing distribution of the predominantly forest subregion, and the forest-grassland and forest-tundra transitions.
Source: Singh and Powell (1986)

productivity, or biomass accumulation rates, in the boreal forest. Also included were non-climatic factors that may be triggered on regulated by climatic events. Information on the atmospheric input of carbon dioxide from burning of boreal forest biomass was also included in the synthesis and bibliography.

A related study was published the following year. Jozsa et al. (1984) used dendroclimatological³ techniques to study how climate affects tree growth in the boreal forest. Their study had a two-fold purpose: (1) to examine the impact of climate on forest biomass production; and (2) to decipher the past climates of the boreal forest. The approach was by means of detailed analyses of tree ring width and tree ring density data. Strong climate-tree growth relationships were found. However, the authors stated that a more sophisticated statistical treatment was required for a better understanding of climate-growth relationships, and for reconstruction of past climates.

4.2.1.1 Microclimate. The research discussed so far has been concerned with large-scale regional climates. A forest stand, and even an individual tree, can modify the climate around it. Therefore, microclimate studies are also needed for forest management. Researchers at the Northern Forest Research Centre studied the effect of clearcutting on the soil temperatures in forests near Hinton, Alberta (Singh 1986). Small increases in surface and subsurface mean temperatures were found in clearcut blocks in July and August. The increase in mean temperatures

³Climate deduced from the properties of tree growth rings.

could be beneficial with adequate moisture supply; the reverse could be true under drought conditions. Such microclimatic changes may be important for the growth and survival of seedlings planted in the clearcut blocks.

4.2.2 Climate and Forest Fires

Forest fires and their rate of spread are direct functions of weather and climate. The fire seasons of 1980 and 1981 were the most severe in Alberta since the beginning of records in 1939. Janz (1982) felt that both seasons provided evidence of the impact of extreme climatic variability on the forest resource. A fire weather index (FWI) was used to compare the two seasons. The frequency of days with a Very High or Extreme index ($FWI \geq 19$) was tabulated for each month. In 1981, almost twice the area of the previous year was burned. Janz attributed this to a coincidence in time between high FWI and an active lightning period. In 1980, a period of severe lightning followed a period of high FWI. The major fires of 1980 were caused by man, whereas the worst fires of 1981 were ignited by lightning. The early spring peak and the late summer peak in Alberta's forest fire hazard reflect seasonal climate changes.

Alberta's lightning climatology was discussed by Nimchuk and Janz (1983). Previous lightning frequency data were derived from the observed number of thunderstorm days per year and the results depended on station density. Experience in 1982 with the new lightning-detection system of the Alberta Forest Service showed that lightning frequencies were much

higher than previously thought in (1) mountainous and plains regions; (2) small convective clouds; and (3) cool fall weather.

4.3 WATER RESOURCES

The physiographic diversity of Alberta, which ranges from the Rocky Mountains and foothills to open prairie; and the contrast in water availability, between northern and southern regions, produces a wide range of water-resource management challenges. Because most components of the hydrologic cycle are climatically controlled, water resource managers must be cognizant of the climatic characteristics and the climatic processes in their region.

4.3.1 Snow

As snow may accumulate for some time before it melts and runs off or is evaporated, it impacts on Alberta's water resources year round. Hence, in addition to the task of measuring how much snow falls, the water resource manager must also determine the rates of snowmelt and evaporation. Snow also has the capacity to retard the runoff from rain and to store a portion of the rainfall and release it to the ecosystem at a later date. Snow management is important to runoff, flood control, irrigation, and energy-balance studies, and has been investigated by many (Barnaby 1980, 1982; Golding 1978; Louie 1977; Nkemdirim and Benoit 1975).

While studying snowfall extremes in Alberta, Nkemdirim and Benoit (1975) found a pattern of high probabilities of large snowfalls in the south and west parts of the province, and in the vicinity of Fort

Vermilion. High-intensity snowfalls occurred most frequently in the fall and spring seasons. The timing of heavy snowfalls is of particular interest to flood control authorities because, during the spring melt period, heavy snow can aggravate existing floods.

Louie (1977) used a modified form of Sverdrup's equation to calculate potential, or theoretical, evaporative loss of snow during chinook seasons (December to March) at Calgary and Lethbridge. He found maximum losses in December and March, with a minimum in January, based on 19 seasons of data. Average values per season were 72 mm at Calgary, and 116 mm at Lethbridge. He concluded that such losses were of hydrological significance in regions with relatively shallow snowpacks.

Golding (1978) studied potential, or theoretical, snow evaporation rates in chinooks in the eastern slopes between Banff and Nordegg. He instrumented three transects in the area with hygrothermographs and anemometers. The resulting evaporation rates in chinooks averaged 1 to 2 mm·day⁻¹ over a two-year period, and ranged up to a maximum of 10 mm·day⁻¹ in a period of very strong winds.

Forecasters at the Alberta Environment River Forecast Centre require accurate and timely data on snowpack conditions and snowmelt variability. Snow courses and a snow pillow network were both used for flood and water supply forecast information (Barnaby 1980, 1982; Coles and Graham 1983).

4.3.2 Evaporation

One of the largest components of the water balance is evapotranspiration. It is also one of the most difficult to measure accurately. Lysimetry is impractical for most sites, so evapotranspiration must be assessed indirectly.

Bothe (1980) used Alberta climatological observations to conduct indirect tests of the Complementary Relationship Lake Evaporation (CRLE), and the Complementary Relationship Areal Evapotranspiration (CRAE) models of Morton (1971, 1975, 1976, 1978, 1979). These models utilize routine observations of air temperature, dewpoint temperature, and sunshine and, for the first time, take into account differences between land and lake environments. The results were encouraging, and the models are now used routinely by Alberta Environment. More recently, Morton (1980, 1983a, 1983b) elaborated on his models and, in 1986, Bothe and Abraham used them to compute monthly values of potential and lake evaporation, as well as potential and areal evapotranspiration for 25 locations in Alberta. These values were updated for the period 1912 to 1985 by Bothe and Abraham (1987). Evapotranspiration values are important for hydrological forecasts of runoff because they make possible quantitative estimates of basin storage changes in a water-balance equation. Furthermore, they are important for irrigation management because they make estimates of the amount of water needed by the soil-plant layer possible so that water supply is no longer a limiting factor in plant growth.

Averaging errors of up to 25 percent, that result from non-linearity effects, and covariance between variables, when monthly

averages of climatological variables are used in Dalton-type evaporation formulas were reported by Hage (1975b), using data from Edmonton International Airport. A simple and crude error correction model was developed.

Enhanced evaporation rates, caused by the release of excess power-plant heat into Lake Wabamun, Alberta, were estimated by Hage (1978) using 21 years of monthly lake-level changes, precipitation, and discharge measurements, coupled with monthly estimates of lake evaporation and runoff. Even after the elimination of systematic errors by subtraction of water-budget equation residuals, fairly large uncertainties remained in the estimated mean enhanced evaporation rates.

4.3.3 Flood Forecasting

Flood forecasting, and the analysis of severe precipitation events, has been aided in Alberta in recent years by weather radar technology. Radar data not only augment the precipitation data from conventional networks, but also can be used to infer rainfall rates and amounts between network stations. A number of publications have explored the use of radar data and its application to water resources management (Barge and Humphries 1977; Humphries 1983; Wojtliw 1986a). Alberta Environment and the Alberta Research Council have directed investigations towards the use of weather radar for streamflow and flood forecasting.

4.4 URBAN CLIMATOLOGY AND AIR POLLUTION

The influence of urban and industrial development on climate has received much attention in recent years. The primary focus has been on urban air quality, although there has also been significant emphasis on the variability of climatological parameters such as temperature and moisture. Consistent changes in urban climates have coincided with the rapid growth of Alberta cities since 1950.

4.4.1 Conditions of the Boundary Layer

The boundary layer is the lowest layer of the atmosphere, where frictional forces from terrestrial features play an important role. In most mid-latitude locations, this layer extends from the surface to 1 km in depth. Turbulent eddies, which exist in the boundary layer, are of primary importance for estimating pollutant dispersion. The turbulent structure of the boundary layer is often analyzed indirectly by looking at the horizontal and vertical distributions of wind and temperature.

Wind climatologies have been completed by various authors for industrial centres in Alberta. Malkiewicz and Portelli (1976) described annual and seasonal wind climatologies of the Athabasca oil sands region. A significant number of wind observations (13.6%) were calm, and the highest frequency of calms occurred in the winter. It was found that topographical influences on airflow were dominant in light prevailing winds.

Denison (1977) looked at air parcel trajectories at the 850 mb level to assess the mean transport of pollutants through the oil sands

region. A large westerly component was found in air parcels both entering and leaving the region. The only exception was in the spring season when 850 mb trajectories were predominantly from southeast and northwest. Leahey and Hansen (1982) also found a dominant westerly component in 850 mb geostrophic wind directions. A large percentage of wind directions were from the northwest and west at 850 mb, becoming westerly and southwesterly near the surface because of frictional influences. The authors concluded from their analysis of differences between geostrophic winds at 1200 m, and measured pilot-balloon winds at 400 m, that terrain effects were appreciable well above the land surface, and many kilometers removed from topographical features.

Several studies have examined the wind structure within and above the cities of Edmonton and Calgary. A Doppler sodar (an acoustical radar) was used by Mathews and Hicks (1984) to measure wind shear, wind speeds, and wind directions at various heights over Calgary. The mean wind speed shear was found to be about $4 \text{ m}\cdot\text{s}^{-1}$ per 100 m, and the mean wind direction change was about 13 degrees per 100 m. Weak anabatic (upslope) and katabatic (downslope) air movements were detected by the sodar.

In other studies, the acoustic sounder was used for continuous qualitative measurements of turbulence in the lower atmosphere (Hicks et al. 1977; Hicks and Mathews 1979; Mathews and Hicks 1979a). By looking at backscatter from acoustic waves interacting with the turbulent temperature fluctuations, it was possible to infer inversion heights and times of inversion breakdown.

When a pipeline carrying sour gas was proposed to traverse a heavily-used recreation area in the Moose Mountain area, 50 km west-southwest of Calgary, a study of the local pollutant dispersion climatology was undertaken (Angle and Gourlay 1983). Information was needed on the characteristic valley airflows because of their effect on the transport and dilution of hydrogen sulphide in the event of an accidental release. The two valleys supported nocturnal drainage flows and weaker up-valley flows during the afternoons. On clear nights, drainage flows filled the valleys, and produced maximum wind speeds of 4 to 7 $\text{m}\cdot\text{s}^{-1}$ halfway between the floor and the rim. Radiation inversions grew to above the valley rims, and persisted from sunset until 3 to 5 hours after sunrise. It was also shown that nocturnal turbulence levels in the valleys were much larger than those over the surrounding plains owing to mechanical production of turbulence in the strong drainage flows. Such turbulence led to much larger air pollutant dilution rates than would be experienced in stable air over level terrain.

The accurate description of microclimatological characteristics of the boundary layer is crucial to the assessment of air pollution dispersion. This is especially important in the vicinity of urban centres. An alternative method of achieving a more complete climatological data set was suggested by Walmsley and Bagg (1978). Missing data from one station can sometimes be replaced by interpolated data, derived from a correlation technique applied to a nearby station.

4.4.2 Urban Heat Island

Increased anthropogenic activities such as industry, development of urban morphology, and transportation, have influenced the urban temperature regime of Alberta cities since they began. Research into the dynamics of the three-dimensional urban temperature structure, or the urban heat island, has been a frequent subject of research for the major urban centres in Alberta, especially since 1965. The number of studies of Calgary's urban heat island increased in the period 1975 to 1986 (Nkemdirim 1975, 1976, 1980a, 1980b; Nkemdirim and Truch 1978; Leggat 1978). Some of the early findings were summarized by Nkemdirim (1977a, 1977b). Using surface observations, he found urban temperatures to be higher than rural temperatures at all hours of the day in contrast to many results elsewhere. He also found two maxima in heat island intensity with a primary maximum in mid-morning, unlike most other cities. It was found that the intensity of Calgary's urban heat island had increased by 80 percent from 1965 to 1975, during a period of 50 percent increase in urban population. Wind speed and direction, combustion heat emission rates, atmospheric stability, and cloudiness explained most of the variance in heat island intensity. These factors were merged into an empirical heat island model.

In a later study, an instrumented helicopter, pilot balloons, and a radiosonde, were added to surface measurements to produce a three-dimensional view of the urban heat island (Leggat 1978). The study revealed that surface temperatures were related to mixing heights, and that an elevated layer of warm air often existed downwind of the city.

Leggat found similar urban stability conditions with both cyclonic and anticyclonic weather systems and, contrary to results from other North American cities, found the mixing layer to be non-adiabatic.

Nkemdirim (1980a) tested models that attempted to relate urban heat island intensity to nearby rural vertical atmospheric temperature gradients and wind speed. The model predictions were compared with data from an instrumented helicopter, pilot balloons, and surface observations. The vertical temperature gradient at the edge of the city was found to be the best predictor.

The influence of the urban fabric is an important factor in determining the three-dimensional temperature structure of the city. Nkemdirim (1980b) concluded that the urban temperature field in Calgary is a multi-celled phenomenon, consisting of warm and cold pockets that are altered by high winds and terrestrial features.

The nocturnal temperature regime and the associated boundary-layer structure of Edmonton was studied by Yap (1975) using helicopters, minisondes, and tower observations for selected days in November and December 1974. He found wide-ranging vertical temperature gradients, including inversion conditions, in what he preferred to call the "urban nocturnal modified layer", and he found that it seldom exceeded 100 m in depth.

The influence of urban growth on humidity in Edmonton was studied by Hage (1975a). Using urban and nearby rural observations during a period of rapid city growth, the city was found to be relatively dry at all hours (relative humidity), and dry by day, but moist by night

(absolute humidity), in all but the winter months. In winter, relative and absolute humidities were higher in the city because of local combustion sources of water vapour interacting with shallow vertical mixing. Annual maxima in absolute humidity differences were found at night in March and August (city moist), and by day in July (city dry). The former differences were attributed to urban snowmelt (March), and to rural dewfall (August). The July peak difference was attributed to rural evapotranspiration.

Studies prior to 1975 had shown increases in the frequency and density of low-temperature fog or ice fog in Edmonton associated with increased residential combustion of natural gas. Data from the cold month of January 1982 were used by Hopper (1986) to show the contribution of water vapour from industrial sources in northeast Edmonton to low visibilities in fog with east and northeast winds.

Nkemdirim (1981) found highly significant variations in summer rainfall within the City of Calgary. However, he was unable to identify the principal reasons for these variations among possibilities such as elevation, wind direction, air pollution, and urban fabric.

4.5 RECREATION/TOURISM

Tourism is a multi-million dollar industry in Alberta, and it has been identified as an area of potential economic growth. Recreational activities are expected to occupy a larger share of an individual's time in the future in response to increased life expectancies, increased part-time employment, introduction of time-saving technology, and other

trends. It is acknowledged that climate is a critical determinant in the supply and demand for recreation and tourism. The climate patterns affect the feasibility, viability, and profitability of both public and private sector investments in the development and operation of recreational programs and facilities.

In 1982, members of the Canadian Climate Program convened to discuss the climate needs for various sectoral activities of the economy (Canada, Environment 1982b). Recreation and tourism was one activity singled out for study. It was recognized that climate affects the choice of activity, participation time, and degree of satisfaction achieved by the participant. Clearly, climate can be of prime importance. Masterton, Crowe, and Baker (1976) authored a major study to determine the relative climatic potential for a variety of recreational activities in the Prairie Provinces. Although not limited to Alberta, it will be discussed in detail because of its importance. Three approaches to understanding the climatic potential for recreation were offered:

1. Delineation of tourism and recreation seasons
2. Outline of the climate conditions necessary for outdoor recreation activities
3. Discussion of major climatic factors which influence outdoor recreation and tourism.

In terms of recreational activities, the traditional division of seasons is not optimal. Masterton, Crowe, and Baker referred only to winter and summer with summer subdivided into spring shoulder, high summer, and autumn shoulder seasons. These seasons are more applicable

to recreation activities. The report contained isopleth maps of the Prairie Provinces showing the length in days of these seasons and how they varied across the region.

Recreational activities were grouped together, as year-round pursuits such as landscape touring, winter pursuits such as skiing and snowmobiling, or summer pursuits such as beach activities. For each activity, the concept of a suitable activity day was developed, together with specific climate conditions that must be satisfied for designation as a suitable day. For example, a suitable day for skiing must have a temperature greater than -15°C , visibility greater than 0.8 km, wind speed less than 25 km/h, and at least 2.5 cm of snowcover. With this information, the number of suitable days per activity was mapped for the Prairie Provinces. The report concluded with a discussion of chinooks, blizzards, and wind chill: conditions which can severely limit outdoor recreational activities in Alberta.

The preceding report was summarized at some length because it was cited repeatedly by later authors as a classic study of climate and recreation. Similar approaches to recreation climate were used by Olson (1985), and Klivokiotis and Thomson (1986) in their descriptions of the climate of the two major urban centres in Alberta; by Cote (1985) in his report on the climate of Kananaskis; and by Charlton (1976) in his contribution towards a plan for Hermitage parksite in Edmonton.

4.5.1 Recreation in the Parks

Resource information, including climate, is of importance in the planning of park sites and facilities. Ideally, climate data would be integrated into the planning process before decisions leading to on-ground facilities are finalized (ACA 1980). The economic costs of a poorly-planned facility can be very large, in terms of annual upkeep, or possible remedial action. Loomis (1980) identified, as most important, the following applications of climatological and meteorological information:

1. To provide the data that are necessary for effective management of park resources;
2. To ensure good facility location and design;
3. To ensure visitor safety;
4. To determine the characteristics of park seasonalities and to spread activities to shoulder periods;
5. To complement the education and interpretation programs; and
6. To assist in the systems planning work of Alberta parks.

Janz and Storr (1977) included a checklist of climatic parameters for site selection in parks. The location of a potential recreation site must be considered in terms of its altitude (solar radiation, exposure), precipitation, temperature extremes, wind, and lightning. In mountain parks, snowfall, wind, and extreme temperatures are of special importance. Cote (1984) also discussed climate in relation to site selection for recreational activities.

4.6 OTHER STUDIES

There are many other fields where climate interacts with human activities. Transportation, construction, and urban planning are examples of topics which would benefit from the application of climate principles.

Very little research has been done in Alberta on the inter-relationships between climate and transportation. Janz and Storr (1977) included a brief discussion. The authors realized that climate information is a secondary concern in the economics of highway design and construction. Nonetheless, precipitation, wind, shading, and frost penetration are but a few of the parameters that should be considered in highway construction.

Climate is important for urban planning too. Angle (1980) stated that "If the climatologist is to contribute effectively to decision making, he must understand the planner's problems . . . The challenge of climatologists and planners lies in the development of practical methods for applying climatological knowledge in the decision-making process." Table 2, from his paper, shows the complexity of climatological concepts and their interactions with associated planning decisions. The point is made, in a discussion of urban planning in Edmonton, that the impact of climate becomes more important, socioeconomically, with intensification of land use. The variables of temperature, wind, and precipitation all have major impacts on snow removal and disposal costs, storm water management, and the microclimate of the central business district. The climate for pedestrians downtown can be significantly different from that for suburban dwellers because of wind channeling and restricted sunlight.

The Canadian Climate Centre recognized a great need to improve communication and information sharing with the construction industry, and to make the industry more aware of how their interests might be better served by paying attention to climatic influences, especially in the area of energy efficiency and conservation(Canada, Environment 1982a).

Table 2. Relations between climate and planning.

Climatological Concepts	Nature of Planning Decisions
mixing height inversion stagnation persistence turbulent mixing roughness topographic airflows ventilation stability wind rose growing season heat units frost-free period sunshine moisture aridity evapotranspiration thermal efficiency precipitation efficiency exposure aspect katabatic wind frost hollow cloudiness fog pocket street canyons wind tunnels heat island day length shading albedo snow drifting wind chill heat load energy input nocturnal cooling illumination comfort	geographical allocation of heavy industry choice of new townsites urban zoning stack design relative location and size of structures regional land use industrial siting agricultural development forest clearing crop selection residential subdivision recreational potential use of uplands, slopes, and valleys location of airports and highways urban zoning height, spacing, orientation, and shapes of buildings and groups of buildings street layout heating and air conditioning orientation and size of windows, skylights, and clerestories insulation amounts overhangs, louvers, shutters, and landscaping reflectivity/emissivity of building materials shelterbelt/windbreaks

Continued . . .

Table 2. Concluded.

Climatological Concepts	Nature of Planning Decisions
wind gusts temperature extremes rainfall intensities snow loading icing	strength of buildings, power lines, roadways, and other structures roof pitch capacity of runoff system (storm sewers, suburban lakes)
thermal stress moisture penetration air pollution ultraviolet light	building materials construction methods maintenance
tornadoes lightning severe weather floods	back-up systems contingencies

Source: Angle, R.P. (1980)

5. CLIMATE CHANGE AND VARIABILITY

5.1 CLIMATE CHANGE IN CANADA

A recent headline in a national newspaper referred to a "revolution in climate". What has occurred in the global atmosphere? A more relevant question is: What is going to take place in the coming decades and in the 21st century? Fossil remains and oil fields attest to different climates in Alberta in past ages. We have convincing evidence of past climates that ranged from frigid ice caps to warm interglacial periods. It is now accepted that the climate has always varied but what is new is the expected rapidity of future climate changes, and the increased vulnerability of human existence, and the human economy, to rapid climate changes. Rapidly rising populations, with their demands for resources and complex urban infrastructures, and with their massive output of waste products, have left mankind more vulnerable than ever to climate. Indeed, our waste products contribute both to our vulnerability to climate, and to the expected climate changes. For example, when we congregate in large cities our waste gases could become harmful when wind speeds are low and temperature inversions are strong. Some of these waste gases such as carbon dioxide, methane, nitrogen oxides, ozone, chlorofluoro- carbons, and perhaps others not yet identified, are responsible for the depletion of the ozone layer and the so-called "greenhouse" effect. Gases that are important in the greenhouse effect are those that are transparent to solar radiation but not to terrestrial radiation. The jury is out with respect to evidence that global warming

from human contribution to the greenhouse effect has actually occurred. Nevertheless, global warming seems inevitable because the radiative properties of these gases are well known, and because numerous careful observations have documented the rapid buildup of their concentrations in the atmosphere. However, the magnitude of the rate of global warming and its impacts on the environment are uncertain at the present time.

What will happen to the climate as these radiatively-active gases continue to accumulate in the air above? For answers we turn to the best available prediction models - the general circulation models of the atmosphere. Given observed past initial conditions these models have successfully reproduced most of the large-scale features of our present climate. Therefore, we have some confidence in their ability to simulate large-scale climate changes associated with future doubling or quadrupling of absorptive gas concentrations. However, we have no similar reasons to be confident of model predictions of climate change for a small region such as Alberta. At the moment, we must plan for a range of possibilities not knowing whether local mean values and variability will increase, decrease, or remain unchanged. We must do all that we can to encourage and support the development and testing of realistic, high-resolution climate prediction models so that these frustrating uncertainties can be reduced.

At the core of the Canadian research into climatic change is the ongoing development of an atmospheric general circulation model at the Canadian Climate Centre. Work continues to improve the parameterization, or representation, of climatic processes, particularly sea/ice feedbacks, cloud formation, and the hydrological cycle. This model will be used to

test different CO₂ scenarios. The resultant changes in climatic variables such as temperature and precipitation will then be studied.

Now, more than ever before in human history, there is real potential for anthropogenic climate change on a global scale. Future short-period climate changes of unknown magnitude can also be expected from volcanic eruptions, or other unpredictable massive injections of particulate matter and gases into the high atmosphere.

5.2 CLIMATE CHANGE IN ALBERTA

The definitive report on climate change in Alberta was written by Longley (1977). He concluded that Alberta's climate in the past has been both warmer and cooler, as well as wetter and drier than at present. There have been seven glacial episodes in the past three billion years, each lasting for 60 to 100 million years. The last glacial period, called the quaternary, began about 300,000 years Before Present (BP). During this time, the glaciers advanced and retreated four times; the last time of retreat about 10,000 BP. Alberta was settled and the economy developed during the most recent fraction of this benign interglacial period.

Longley examined temperatures and precipitation during the past 100 years in the Prairie Provinces. In Calgary, the warmest decade was 1913 to 1922. Wetaskiwin and Lacombe both peaked in the early 1940s. At Beaverlodge, 1937 to 1946 was the warmest decade. Data from reporting stations in the South Saskatchewan River basin showed precipitation maxima in the 1910s and 1950s, with low levels during the early 1920s.

Longley discussed several additional topics including: causes of recent climatic change, the observed trends in minimum temperatures, and future prospects for significant temperature changes.

Changes in climate and climate variability have not received a lot of attention in Alberta until recently. Schweger et al. (1981) undertook a systematic survey of fossil pollen, fossil diatoms, and the sediment chemistry of Alberta lakes in the foothills, parkland, and southern boreal forest. Some of their findings have yielded important paleoclimatic and paleohydrologic records. Briefly, it was found that, in glacial times, tundra vegetation emerged first in the unglaciated foothills of southern Alberta. This expanded northward as the ice retreated. Rapid warming began about 11,000 BP, and continued unabated until about 9,000 BP, when drought and high evaporation rates dropped the lake levels, and enabled vegetation to expand further to the north. The drought continued until about 6,000 BP. The climate of central Alberta became significantly cooler and wetter around 4,000 BP, thereby establishing the modern climate and vegetation. A lesson from this is that the climate of Alberta, known to be subject to brief droughts, has also experienced lengthy droughts that were measured in thousands of years.

Powell (1981) identified a need to measure and understand the impact of climate, especially climatic fluctuations, on forest biomass productivity. He also identified a need for long-term inventories of biomass in forested areas, with projections of annual yields. The first step in this direction was the literature survey of impact of climatic

variations on biomass accumulation in the boreal forest zone (Peterson et al. 1983). A second step was taken by Singh and Powell (1986) in their analysis of monthly and annual temperature and precipitation data (1872 to 1981) in each of the forest-grassland, forest, and forest-tundra subregions of the boreal forest. They found statistically significant differences between subregions, and slight but significant increasing trends in temperature and precipitation in the forest subregion.

Much of the recent research on the impacts of climate change has used hypothetical scenarios wherein temperature, or precipitation amounts, are altered, a computer simulation of the perturbed climate is produced, and its impacts examined. Bootsma et al. (1984) used a crop-growth model to estimate dry matter yields for cereal, oilseed, potato, forage, and corn crops at several Canadian locations. The Peace River region was the Alberta site chosen for study. Dry-matter yields decreased for all crops with mean temperature changes of $\pm 1^{\circ}\text{C}$ with no precipitation change, and for precipitation changes of 80 to 120 percent with no temperature change, with the following exceptions. Forage yields increased with a cooling of 1°C , but no change in precipitation, and increased with a precipitation increase of 20 percent accompanied by no temperature change. Cereal and potato yields increased with a temperature rise of 1°C , but no change in precipitation.

Climate models and different CO_2 scenarios were used by Williams (1985) to estimate bio-resource sensitivity to climate change in Alberta. His results suggested that climate warming would increase dry-matter productivity in northern Alberta, but reduce productivity somewhat in the relatively warm, dry southeastern part of the province because of the associated increase in moisture stress. Estimates of

yield changes resulting from changes in precipitation clearly demonstrated the moisture limitations of Alberta. For each increment of precipitation increase from 70 percent to 110 percent of normal, the dry-matter yields increased at all sample points in the province, regardless of accompanying temperature changes in the range from -1°C to $+4^{\circ}\text{C}$. Williams pointed out that climate change impact assessment in Canada is difficult because of the shortness of the instrumental record, the relatively high degree of sensitivity to climate change, and the sparseness of the climate station network.

5.3 THE IMPACT ON ALBERTA RESOURCES

In 1981, the Canadian Council of Resource and Environment Ministers held a climate-change seminar, at which Leggat and his colleagues from Alberta presented a paper which discussed the impact of climate change and variability on Alberta's resources and environment (Leggat et al. 1981). The individual sectors of agriculture, air, fish and wildlife, forestry, and water were discussed in detail. It was shown that Alberta's vulnerability to climate variations could have serious ramifications for the successful management of the province's resources and environment. Three priority needs to decrease the impact of climate fluctuations were identified. These were: (1) improved data bases - including the collection of more relevant data; improved archiving, retrieval, and dissemination of data; increased utilization of existing data, and increased cooperation among government agencies; (2) improved "weatherproofing" by policy development to insulate individual sectors of

the economy against detrimental impacts; and (3) improved forecasts in the 1- to 10-year range.

6. SUMMARY

A compilation and synthesis of some 250 reports and publications on climate, and applications of climate, in Alberta in the 12-year period (1975 to 1986) has revealed some notable achievements and some gaps. The total number of studies was comparable to the number that appeared in the 13-year period ending in 1969 (Longley and Powell 1971). The numbers of studies of the applications of climate in agriculture, forestry, and water resources were similar in the two time periods, but the earlier period featured many more analyses of mean values and frequency distributions of climate variables, including many of importance in building design and construction. More studies of climate in relation to crop and forest pests were noted also in the early period. The period 1975 to 1986 featured significant increases in work on climate in relation to forest and agricultural land classification, urban climates, and the urban climate of the Athabasca oil sands region. Recent years have also produced the first studies in Alberta of possible impacts of future climate change, and some descriptions of the impacts of climate on recreation and tourism.

The period 1975 to 1986 witnessed the appearance of new climatologies of Calgary, Edmonton, Banff National Park, Jasper National Park, and Kananaskis, that were much more comprehensive than those available previously. Climatic classification of agricultural and forest lands became more detailed and sophisticated through applications of multivariate statistical procedures, and through attempts to take a holistic approach to climate, vegetation, soils, and land use. Future

planning of climate station networks was enhanced by the assembly of a climate station catalogue, publication of a network planning document, and an assessment of data collection and handling procedures. A need for a provincial central facility for coordination and archiving of climate measurements was identified.

Improved awareness and understanding of user needs was apparent in several studies. The specific needs of building designers and engineers were recognized by the methods of collection and analysis of solar radiation data over Edmonton. Special wind and solar radiation measurements were undertaken specifically for work on renewable energy. Spatial and temporal variations in the cube of surface wind speeds were published for the benefit of soil erosion researchers. Statistical analyses of historical severe rainfall events in Alberta have simplified the work of hydrologists on probable maximum precipitation and probable maximum floods, and we can expect to see many more such studies in the future. Nevertheless, much remains to be done to improve communication and understanding between climate researchers and climate information users. The importance of a clear understanding of user needs cannot be overemphasized in climate research.

Provincial groups such as the Alberta Climatological Association, the Alberta Climate Advisory Committee, and the Advisory Committees on Soils and Agrometeorology of Alberta Agriculture have performed admirably in breaking down barriers of communication and understanding. As an example of productive committee work, the Agrometeorology Advisory Committee provided the Soils Advisory Committee with new formulations of climatic factors that were then introduced

into a system for classification of arable land for agriculture. The annual meetings of the Alberta Climatological Association and its publications promoted research progress and efficiency by attempting to cross the boundaries of conventional disciplines. These groups deserve wider public recognition for their efforts to make interdisciplinary research a reality in climate impact studies.

Costly difficulties with data acquisition systems were encountered both in the solar and wind energy measurement program and in the Athabasca oil sands automatic weather station program. The costs here were greatest, perhaps, in the failure of the measurement programs to provide data of sufficient quantity and quality to meet the original objectives of the projects. Extra resources for pre-testing and for redundancy provisions would often be well spent. Increased benefits could be realized also, perhaps, if the overall needs of the research community were better known. For example, it is possible that the needs of soil erosion researchers for more wind data in certain areas of the province could have been met to some extent by station location adjustments in the solar and wind energy program.

Following early two-dimensional descriptive studies, recent research on chinooks and urban climates turned to aircraft, helicopters, towers, and remote sensing for time-dependent three-dimensional views. At this time, there appears to be a need for realistic computer simulation models of chinooks and urban heat islands to test hypotheses and to guide future measurement programs. There is a need also for a better understanding of user interests by researchers in these fields so that

more of the past results can be applied. Two results of practical interest were: (1) the conclusion that hydrologically-significant evaporative losses occurred from shallow snowpacks during chinooks, and (2) that significantly lower visibilities in low temperature fog in Edmonton have resulted from industrial water vapour emissions in east to northeast winds. The relationship, if any, between chinooks and air quality in Calgary needs clarification. Other climate-related urban problems such as icing of street intersections and bridges in cold weather remain to be studied.

New estimates of evapotranspiration and lake evaporation have been computed for many locations in Alberta for the period 1912 to 1985 and are now available for runoff and irrigation studies. It would be useful to know how these estimates compare in accuracy with previous estimates for individual sites and regions within the province. The capabilities of radar for remote sensing of rainfall and rainfall rates have been well documented but not yet fully exploited. The climatology of hail in central Alberta is now known more fully, perhaps, than that of any other hail-prone region of the world. We now know, too, that a few hours of hail in a city like Calgary can cause as much economic loss as a full season of hail in rural Alberta.

The impacts of possible climatic changes in Alberta received some attention in 1975 to 1986, but much remains to be done. One approach has been to estimate changes in crop or dry-matter yields corresponding to small decreases or increases in temperature or precipitation. In such work, it is important to demonstrate that the

crop models show substantial skill in yield predictions without climate change, and that predicted yield changes are statistically significant as predictions. Furthermore, the validity of using single variable changes, for example, an increase in temperature with no change in precipitation, or an increase in precipitation with no change in cloudiness, seems open to question. Sensitivity studies are needed as well as response studies. This may be an opportune time to conduct a critical review of the performance and sensitivity of crop and forest biomass yield prediction models for plant species of interest in Alberta. The recent annotated bibliography and synthesis of forest biomass accumulation rates, prepared for the Northern Forest Research Centre, may be useful in this regard. It should certainly be an asset in other studies of forest climatology. The bibliography includes the topic of carbon dioxide production by burning of boreal forest biomass.

At some time in the coming decade, it may be opportune also to produce an updated review of climate change in Alberta which will summarize sensitivity and responses studies, and examine critically some of the reports of observed trends in temperature, precipitation, and other climatic variables.

The period 1975 to 1986 saw little research on the impacts of climate on construction, transportation, recreation, and tourism. Only two studies reported on indoor climate or the climate of enclosed spaces despite concerns about energy consumption and indoor air quality, and despite some trends in agriculture towards mixed farming, organic farming, food processing, and increased use of greenhouses. It is

possible, of course, that such studies were carried out but were missed by our literature search procedures.

7. REFERENCES

7.1 CITED REFERENCES

- Admirat, P., G.G. Goyer, L. Wojtiw, E.A. Carte, D. Roos, and E.P. Lozowski. 1985. A comparative study of hailstorms in Switzerland, Canada, and South Africa. *Journal of Climatology* 5:35-51.
- Ahmadi, G. and P.G. Glockner. 1984. Dynamic simulation of the performance of an inflatable greenhouse in the southern part of Alberta. III. Effects of cloudiness factors. *Agricultural and Forest Meteorology* 31:183-191.
- Alberta Climatological Association. 1977. Applications of climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Edited by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. 93 pp.
- Alberta Climatological Association. 1978. Climatic networks. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1978 April 13. Edmonton, Alberta. Compiled by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-209. 101 pp.
- Alberta Climatological Association. 1980a. Socioeconomic impacts of climate. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1979 March 02. Edmonton, Alberta. Compiled by J.M. Powell. Environment Canada, Northern Forest Research Centre. Information Report NOR-X-217. 101 pp.
- Alberta Climatological Association. 1980b. Proceedings for the 1980 Annual Meeting of the Alberta Climatological Association. 1980 February 29. Edmonton, Alberta. Edited by K.R. Leggat. Alberta Energy and Natural Resources. Technical Report T/10-1980. 56 pp.
- Alberta Climatological Association. 1981. The impacts of climatic fluctuations on Alberta's resources and environment. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1981 February 26. Edmonton, Alberta. Compiled by K.R. Leggat and J.T. Kotylak. Environment Canada, Atmospheric Environment Service Report No. WAES-1-81. 107 pp.
- Alberta Climatological Association. 1982. Current climatological activity in Alberta. Proceedings of the Technical and Business Sessions of the 6th Annual General Meeting of the Alberta Climatological Association. 1982 February 25. Edmonton, Alberta. Compiled by Bill Kuhnke. Alberta Environment. 87 pp.

- Alberta Climatological Association. 1983. Current climatological activity in Alberta. Proceedings of the 7th Annual Workshop of the Alberta Climatological Association. 1983 February 24. Edmonton, Alberta. Alberta Agriculture. 106 pp.
- Alberta Climatological Association. 1984. Current climatological activity in Alberta. Proceedings of the 8th Annual Workshop of the Alberta Climatological Association. 1984 February 25. Edmonton, Alberta. Compiled by Serge Dupuis. Alberta Energy and Natural Resources. 148 pp.
- Alberta Climatological Association. 1985. Current climatological activity in Alberta. Proceedings of the 9th Annual General Meeting of the Alberta Climatological Association. 1985 June 04. Edmonton, Alberta. Compiled by Serge Dupuis. Alberta Energy and Natural Resources. 140 pp.
- Alberta Climatological Association. 1986. Current climatological activity in Alberta. Proceedings of the 10th Annual General Meeting of the Alberta Climatological Association. 1986 February 20. Edmonton, Alberta. 116 pp.
- Alberta Energy and Natural Resources. 1985. Alberta climate station catalogue. Resource Evaluation and Planning Division. Compiled by Climate Unit, Resource Information Services, Resource Evaluation Branch. 150 pp.
- Alberta Environment. 1974. Alberta oil sands climatological and meteorological research. Prepared by the Conservation and Utilization Committee, Oil Sands Climatological and Hydrological Research Task Force. 15 pp.
- Alberta Research Council. 1986. Solar and wind energy monitoring project 1977-1985. Final Report. Compiled and Edited by Civil Engineering Department. Edmonton, Alberta. 194 pp.
- Alberta Soils Advisory Committee. 1986. Land capability classification for arable agriculture in Alberta (1986): a working document. Edited by W.W. Pettapiece. Alberta Agriculture. Edmonton, Alberta. 89 pp.
- American Society of Heating, Refrigerating and Air Conditioning Engineers. 1977. Handbook of Fundamentals. Chapter 26. Fenestration. New York, New York. pp. 26.1-26.38.
- Angle, R.P. 1980. Climate and planning: The need for practical techniques. In: Socioeconomic impact of climate. Proceedings of the Workshop and 3rd Annual Meeting of Alberta Climatological Association. 1979 March 02. Edmonton, Alberta. Compiled by J.M. Powell. Northern Forest Research Centre. Information Report NOR-X-217. pp. 60-66.

- Angle, R.P. and P. Gourlay. 1983. Dispersion climatology of the Moose Mountain area. Alberta Environment, Pollution Control Division. 58 pp.
- Arrhenius, S. 1896. On the influence of the carbonic acid in the air upon the temperature of the ground. Philosophical Magazine and Journal of Science Series 5, 41:237-276.
- Bailey, W.G. 1981. The climate resources for agriculture in north-western Canada. Agriculture and Forestry Bulletin 4:11-17.
- Barge, B.L. and R.G. Humphries. 1977. Precipitation measurement by weather radar. In: Applications of climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Edited by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 34-64.
- Barlow, F.D., R.H. Myrick, F.E. Robitaille, J.H. Renick. 1986. Micro-physical characteristics of winter clouds over the southern Canadian Rockies. In: Preprint volume: 10th Conference on Planned and Inadvertent Weather Modification. 1986 May 27-30. Arlington, Virginia. American Meteorological Society. pp. 110-114.
- Barlow, F.D., F.E. Robitaille, J.W. Mason, and C.M. Sackiw. 1983. Snow climatology of the southern Canadian Rockies. In: Papers presented at the 17th Annual Canadian Meteorological and Oceanographic Society Congress. May 1983. Banff, Alberta. Alberta Research Council, Atmospheric Sciences Department. 11 pp.
- Barnaby, I.E. 1980. Snowmelt observations in Alberta. In: Proceedings of the Western Snow Conference 48th Annual Meeting. 1980 April 15-17. Laramie, Wyoming. Colorado State University, Fort Collins, Colorado. pp. 128-137.
- Barnaby, I.E. 1982. Utilization of snow course and snow pillow data in Alberta. In: Current climatological activity in Alberta, Proc. of the Technical and Business Sessions of the 6th Annual General Meeting of the Alberta Climatological Association. 1982 February 25. Edmonton, Alberta. Compiled by Bill Kuhnke. Alberta Environment. 87 pp.
- Bootsma, A., W.J. Blackburn, R.B. Stewart, R.W. Muma, and J. Dumanski. 1984. Possible effects of climatic change on estimated crop yields in Canada. Agriculture Canada Research Branch. Technical Bulletin 1984-9E. Ottawa, Ontario. 26 pp.
- Bothe, R.A. 1980. Assessment of F.I. Morton's model of lake evaporation. Alberta Environment, Hydrology Branch. 28 pp.

- Bothe, R.A. and C. Abraham. 1987. Evaporation and evapotranspiration in Alberta 1912 to 1985. Alberta Environment, Hydrology Branch. 21 pp. + Appendices.
- Canada. Environment. 1982a. Needs and recommendations and a plan for action. Canadian Climate Program. 62 pp.
- Canada. Environment. 1982b. Climate Advisory Committee annual program review meeting. 1982 May 13-14. Hull, Quebec. Canadian Climate Program. 72 pp.
- Canadian National Committee for the International Union of Geodesy and Geophysics. 1987. Canadian geophysical bulletin. Volume 40. Edited by P.B. Robertson. Ottawa, Ontario. Energy, Mines and Resources Canada, Geological Survey of Canada. 174 pp.
- Chamberlin, T.C. 1899. An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis. Journal of Geology 7:545-584, 667-685, 751-787.
- Charlton, R.B. 1976. Climate, air quality and noise at the proposed Hermitage parksite. Environmental impact statement by LGL Ltd. for Edmonton Parks and Recreation. Edmonton, Alberta. 90 pp.
- Charlton, R.B., B. Janz, and J. Toogood. 1976. Climate of Alberta. In: Alberta Farm Guide. Alberta Agriculture, Extension Service. pp. 5-17.
- Chen, R. S. and M. L. Parry (Editors). 1987. Policy-oriented impact assessment of climatic variations. International Institute for Applied Systems Analysis. Laxenburg, Austria. 54 pp.
- Coles, G.A. and D.R. Graham. 1983. Alberta Environment real time hydro-meteorological network current status. In: Current climatological activity in Alberta. Proceedings of the 7th Annual Workshop of the Alberta Climatological Association. 1983 February 24. Edmonton, Alberta. Alberta Agriculture. pp. 13-31.
- Cote, M. 1984. The climate of Kananaskis. Internal document. Prepared for Atmospheric Environment Service. Edmonton, Alberta. 126 pp.
- Davies, C.S., P. Fellin, D. Stevens, S. Todd, and K. Heidorn. 1985. Evaluation, analysis, and assessment of snowpack and precipitation data from a monitoring network in the AOSERP study area. Prepared for Alberta Environment, Research Management Division by Concord Scientific Corporation. RMD Report 86/36. 341 pp.

- Denison, P.J. 1977. A climatology of low-level air trajectories in the Alberta oil sands area. Prepared by Acres Consulting Services for the Alberta Oil Sands Environmental Research Program. AOSERP Report 15. 118 pp.
- Drews, M.D. 1981. An aid to forecasting chinooks over southern Alberta. Environment Canada, Atmospheric Environment Service. Downsview, Ontario. 20 pp.
- Dupuis, S. 1982. Evaluating agricultural potential in the Peace River region, the climate inventory program. In: Current climatological activity in Alberta. Proceedings of the Technical and Business Sessions of the 6th Annual General Meeting of the Alberta Climatological Association. 1982 February 25. Edmonton, Alberta. Compiled by Bill Kuhnke. Alberta Climatological Association. 87 pp.
- Dupuis, S. 1983. Calculation of agroclimatic statistics from short-term networks. In: Current climatological activity in Alberta. Proceedings of the 7th Annual Workshop Alberta Climatological Association. 1983 February 24. Edmonton, Alberta. Alberta Agriculture. pp. 3-12.
- Ekistic Design Consultants Ltd. 1975. Northeast Alberta regional plan - a working document on climate and the northeast Alberta regional plan. 45 pp.
- Figliuzzi, S.J. 1982. Probable maximum flood for the Battle River near Gwynne. Alberta Environment, Hydrology Branch. 80 pp.
- Findlay, B. 1981. Drought in the Alberta perspective. In: The impact of climatic fluctuations on Alberta's resources and environment. Proc. of the Workshop and Annual Meeting of the Alberta Climatological Association. 1981 February 26. Edmonton, Alberta. Compiled by K.R. Leggat and J.T. Kotylak. Environment Canada, Atmospheric Environment Service. Report No. WAES-1-81. pp. 23-46.
- Fletcher, F.J. 1972. The climate of southern Alberta. In: Southern Alberta - a regional perspective. Edited by F. Jankunis. Unilith Press, Lethbridge, Alberta. pp. 20-34.
- Gietz, C.W. 1983. Erosive potential of wind in Alberta. In: Current climatological activity in Alberta. Proceedings of the 7th Annual Workshop of the Alberta Climatological Association. 1983 February 24. Edmonton, Alberta. Alberta Agriculture. pp. 49-62.
- Gilpin, R.R. 1977. The use of south facing windows for solar heating in a northern climate. Paper presented to the 3rd Annual General Meeting and Conference of the Solar Energy Society of Canada. 1977 August 22-24. Edmonton, Alberta. 12 pp.

- Glantz, M., R. Katz, and M. Krenz (Editors). 1987. The societal impacts associated with the 1982-83 worldwide climate anomalies. National Center for Atmospheric Research, Environmental and Societal Impacts Group. Boulder, Colorado, USA. 105 pp.
- Golding, D L. 1978. Calculated snowpack evaporation during chinook along the eastern slopes of the Rocky Mountain in Alberta. *Journal of Applied Meteorology* 17:1647-1651.
- Gourlay, P. 1985. An overview of solar radiation data collection and applications in Alberta. Alberta Environment, Research Management Division. Edmonton, Alberta. RMD Report L-88. 23 pp.
- Grace, B. 1986. Recent weather on the Canadian Prairies and its effects on agriculture. In: *Proceedings of the 5th Annual Western Provinces Conference Rationalization of Soil and Water Research and Management*. 1986 November 18-20. Calgary, Alberta. pp. 26-49.
- Hage, K.D. 1975a. Urban-rural humidity differences. *Journal of Applied Meteorology* 14:1277-1283.
- Hage, K.D. 1975b. Averaging errors in monthly evaporation estimates. *Water Resources Research* 11:359-361.
- Hage, K.D. 1977. Local history as source of climatic information. In: *Applications of Climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee*. 1977 March 04. Edmonton, Alberta. Edited by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 11-28.
- Hage, K.D. 1978. Natural and enhanced evaporation from Lake Wabamun, Alberta. *Canadian Water Resources Journal* 3:49-61.
- Hage, K.D. 1984. Western prairie tornadoes: evil spirits to acts of God. Paper presented to the Alberta Centre of the Canadian Meteorological and Oceanographic Society. 1984 December 13. Edmonton, Alberta. 26 pp.
- Hage, K.D. 1985. Weather extremes in Alberta: 1880 to 1960. *Climatological Bulletin* 19:3-15.
- Hansen, M.C. and M.D. Jones. 1983. An assessment of collection and handling of climate data by Alberta Government agencies. Prepared by Western Research, Division of Bow Valley Resource Services Ltd. for Alberta Environment, Research Management Division. Edmonton Alberta. RMD Report 82/12. 45 pp.

- Hay, J.E. 1977. A tabulation and analysis of solar radiation data for Alberta. Prepared for Alberta Research Council and Alberta Environment. Edmonton, Alberta. 124 pp.
- Hay, J.E. and P.W. Suckling. 1978. Problems associated with the determination of solar radiation fluxes in the Cordilleran region of western Canada. In: Essays on meteorology and climatology: In honour of Richmond W. Longley. Edited by K.D. Hage and E.R. Reinelt. University of Alberta, Department of Geography Monograph 3. Edmonton, Alberta. pp. 71-94.
- Hicks, R.B., D. Smith, P.J. Irwin, and T. Mathews. 1977. Preliminary results of atmospheric sounding at Calgary. Boundary-Layer Meteorology 12:201-212.
- Hicks, R.B. and T. Mathews. 1979. Impact of chinooks on Calgary's air quality: acoustic sounder observations of atmospheric stability. Water, Air and Soil Pollution 11:159-172.
- Hobbs, E.H. 1977. The agricultural climate of the Lethbridge area, Agriculture Canada Research Station. Lethbridge, Alberta. 14 pp.
- Hopper, J.F. 1986. Urban visibilities at low temperatures. Atmospheric Environment 20:1819-1823.
- Humphries, R.G. 1983. The Alberta Research Council weather radar for flood forecasting project. In: Current climatological activity in Alberta. Proceedings of the 7th Annual Workshop of the Alberta Climatological Association. 1983 February 24. Edmonton, Alberta. Alberta Agriculture. pp. 39-47.
- Janz, B. 1977. Estimation of average precipitation in the mountain parks. In: Proceedings of the Symposium on the Alberta Watershed Research Program Symposium. 1977 August 31 to September 01. Edmonton, Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-176. pp. 178-186.
- Janz, B. 1982. Comparison of the 1980 and 1981 fire seasons in Alberta. In: Current climatological activity in Alberta. Proceedings of the Technical and Business Sessions of the 6th Annual General Meeting of the Alberta Climatological Association. 1982 February 25. Edmonton, Alberta. Compiled by Bill Kuhnke. Alberta Environment. pp. 43-52.
- Janz, B. and D. Storr. 1977. The climate of the contiguous mountain parks - Banff, Jasper, Yoho, and Kootenay. Prepared for Parks Canada, Department of Indian and Northern Affairs by Environment Canada, Atmospheric Environment Service. Report No. 30. 325 pp.

- Jozsa, L.A., M.L. Parker, P.A. Bramhall, and S.G. Johnson. 1984. How climate affects tree growth in the boreal forest. Prepared for Environment Canada, Northern Forest Research Centre by Forintek Canada Corporation. Information Report NOR-X-255. 67 pp.
- Kerr, W.E. and P. Papirnik. 1985. The application and worth of climate data in Alberta. Paper presented at the Saskatchewan Climate Advisory Committee's Workshop on the Worth of Climate Data. 1985 October 10. Regina, Saskatchewan. 22 pp.
- Klivokiotis, P. and R.B. Thomson. 1986. The climate of Calgary. Climatological Studies Number 38. The Climate of Canadian Cities Number 3. Canadian Climate Program. 52 pp.
- Laycock, A.H. 1978. Precipitation mapping in Alberta. In: Essays on meteorology and climatology: In honour of Richmond W. Longley. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. Edmonton, Alberta. pp. 133-149.
- Leahey, D.M. and M.C. Hansen. 1982. Influences of terrain on plume level winds in the Athabasca oil sands area. Atmospheric Environment 16:2849-2854.
- Leggat, K.R. 1978. Vertical temperature structure of Calgary's urban heat island. University of Calgary, Department of Geography. Calgary, Alberta. 147 pp. M.Sc. Thesis.
- Leggat, K.R. 1981. Winter climate of the Muskeg River-Huckleberry Tower area 1980-81. Prepared by Alberta Energy and Natural Resources, Resource Evaluation and Planning Division for Fish and Wildlife Division. Edson, Alberta. 24 pp.
- Leggat, K.R., B.L. Magill, N. Van Waas, and H.S. Sandhu. 1981. The impacts of climatic change and variability of Alberta's resources and environment. Paper presented at the Climate Change Seminar of the Canadian Council of Resource and Environmental Ministers. 1981 March 17-19. Regina, Saskatchewan. 20 pp.
- Lester, P.F. 1975. A case study of the Alberta chinook. Paper presented at the Ninth Annual Congress of the Canadian Meteorological and Oceanographic Society. 1975 May 28-30. Vancouver, British Columbia. 40 pp.
- Lester, P.F. 1976a. The chinook of southern Alberta: A problem assessment. Paper presented at the 10th Annual Congress of the Canadian Meteorological and Oceanographic Society. 1976 May 25-28. Quebec City, Quebec. 35 pp.
- Lester, P.F. 1976b. Evidence of long lee waves in southern Alberta. Atmosphere 14:28-36.

- Lester, P.F. 1978. A severe chinook windstorm. Paper presented at the conference on Sierra Nevada Meteorology; 1978 June 19-21. South Lake Tahoe, California. 14 pp.
- Lester, P.F. and J.I. McPherson. 1977. Waves and turbulence in the vicinity of a chinook arch cloud. *Monthly Weather Review* 105:1447-1457.
- Loomis, S.R. 1980. The role of climate in Alberta Provincial Parks planning. In: Socioeconomic impacts of climate. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1979 March 02. Edmonton, Alberta. Compiled by J.M. Powell, Environment Canada, Northern Forest Research Centre. Information Report NOR-X-217. pp. 43-45.
- Longley, R.W. 1967. The frost-free period in Alberta. *Canadian Journal of Plant Science* 47:239-249.
- Longley, R.W. 1972. The climate of the prairie provinces. Environment Canada, Atmospheric Environment Service. Climatological Studies No. 13. 79 pp.
- Longley, R.W. 1977. Climate change as it affects Alberta and the other prairie provinces. Alberta Environment, Research Secretariat. 33 pp.
- Longley, R.W. and J.M. Powell (Editors). Bibliography of climatology for the prairie provinces, 1957-1969. The University of Alberta, Department of Geography, Studies in Geography, Bibliography 1. 64 pp.
- Longley, R.W. and B. Janz. 1978. The climatology of the Alberta Oil Sands Environmental Research Program study area. Prepared for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 39. 102 pp.
- Louie, P.Y.T. 1977. Potential evaporative loss from snow in southwestern Alberta. In: Proceedings of the Canadian Hydrology Symposium. Ottawa, Ontario. National Research Council of Canada, Associate Committee on Hydrology. pp. 24-32.
- MacIver, D.C., W.D. Holland, and J.M. Powell. 1972. Delineation of similar summer climatic regimes in central Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-30. 32 pp.
- Major, D.J. 1977. Corn maturity and weather in Alberta. In: Proceedings of the Symposium of the Agrometeorology of the Maize Crop. Ames, Iowa. WMO-481. pp. 67-75.

- Makowsky, D. 1982. Calgary hailstorm, 1981 July 28. In: Current climatological activity in Alberta. Proceedings of the Technical and Business Sessions of the 6th Annual General Meeting of the Alberta Climatological Association. 1982 February 25. Edmonton, Alberta. Compiled by Bill Kuhnke. Alberta Environment. pp. 39-41.
- Malkiewicz, A.W. and R.V. Portelli. 1976. A climatological study of the air pollution potential of the Alberta oil sands region. Fisheries and Environment Canada, Atmospheric Environment Service. Report ARQT-3-76. 61 pp.
- Marantz, D.M., L.M. Kryzanowski, and K.R. Cannon. 1986. The effect of selected climatological parameters on yield of barley and the modification of nitrogen fertilizer recommendations for barley using climatological data. In: Current climatological activity in Alberta. Proceedings of the 10th Annual General Meeting of the Alberta Climatological Association. 1986 February 20. Edmonton, Alberta. pp. 30-46.
- Masterton, J.M., R.B. Crowe, and W.M. Baker. 1975. The tourism and outdoor recreation climate of the prairie provinces. Fisheries and Environment Canada, Atmospheric Environment Service. Publications in Applied Meteorology REC-1-75. 221 pp.
- Mathews, T. and R.B. Hicks. 1979a. A study of the stability of the atmospheric boundary layer as revealed by an acoustic sounder and its relation to pollution levels in Calgary. Prepared for Alberta Environment, Research Secretariat. Edmonton, Alberta. 5 pp.
- Mathews, T. and R.B. Hicks. 1979b. Typical features of atmospheric turbulence profiles associated with chinooks. Atmosphere-Ocean 17(2):125-134.
- Mathews, T. and R.B. Hicks. 1984. Doppler sodar measurements of wind climatology of Calgary. Prepared for Alberta Environment, Research Management Division. RMD Report 84/28. 149 pp.
- Mathews, T., P.F. Lester, and R.B. Hicks. 1984. Sodar observations of chinooks and arctic front passages across the eastern slopes of the Canadian Rockies. Atmosphere-Ocean 22:328-342.
- Meeres, L.S. 1978. An objective approach to climatic network planning. In: Climatic networks. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1978 April 13. Edmonton, Alberta. Compiled by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-209. pp. 9-16.
- Morton, F.I. 1971. Catchment evaporation and potential evaporation-further development of a climatologic relationship. Journal of Hydrology 12:81-99.

- Morton, F.I. 1975. Estimating evaporation and transpiration from climatological observation. *Journal of Applied Meteorology* 14:488-497.
- Morton, F.I. 1976. Climatological estimates of evapotranspiration. *Journal of the Hydraulics Division, American Society of Civil Engineering* 102(HY3):275-291.
- Morton, F.I. 1978. Estimating evapotranspiration from potential evaporation: practicability of an iconoclastic approach. *Journal of Hydrology* 38:1-32.
- Morton, F.I. 1979. Climatological estimates of lake evaporation. *Water Resources Research* 15:64-76.
- Morton, F.I. 1980. Comments on a diagnostic examination of a complementary relationship between actual and potential evapotranspiration. *Journal of Applied Meteorology* 19:342-345.
- Morton, F.I. 1983a. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology* 66:1-76.
- Morton, F.I. 1983b. Operational estimates of lake evaporation. *Journal of Hydrology* 66:77-100.
- Munn, R.E. 1970. *Biometeorological methods*. Academic Press. New York, New York. 336 pp.
- Munro, D.S. 1975. Energy exchange on a melting glacier. McMaster University, Hamilton, Ontario. Ph.D. Thesis (Original not seen; information taken from Oke 1978).
- National Research Council, Commission on Physical Sciences, Mathematics, and Resources. 1982. Carbon dioxide and climate: A second assessment. Report of the CO₂ Climate Review Panel to the Climate Research Committee of the Climate Board/Committee on Atmospheric Sciences and the Carbon Dioxide Assessment Committee of the Climate Board. National Academy Press, Washington, D.C. 72 pp.
- Newark, M.J. 1984. Canadian tornadoes 1950-1979. *Atmosphere-Ocean* 22:343-353.
- Nimchuk, N. and B. Janz. 1983. The lightning climatology of Alberta - some new insights. In: Current climatological activity in Alberta. Proceedings of the 7th Annual Workshop Alberta Climatological Association. 1983 February 24. Edmonton, Alberta. Alberta Agriculture. pp. 33-38.
- Nkemdirim, L.C. 1975. Calgary's urban heat island. The University of Calgary, Calgary, Alberta. Weather Research Monographs No. 1. 113 pp.

- Nkemdirim, L.C. 1976. Dynamics of an urban temperature field - a case study. *Journal of Applied Meteorology* 15:818-828.
- Nkemdirim, L.C. 1977a. Research in urban climatology at the University of Calgary. *Climatological Bulletin* No. 22. pp. 19-23.
- Nkemdirim, L.C. 1977b. Urban heat island in Calgary: diurnal pattern and time trends. Applications of climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Edited by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 69-77.
- Nkemdirim, L.C. 1978. A comparison of radiative and actual nocturnal cooling rates over grass and snow. *Journal of Applied Meteorology* 17:1643-1646.
- Nkemdirim, L.C. 1980a. A test of a lapse rate/wind speed model for estimating heat island magnitude in an urban airshed. *Journal of Applied Meteorology* 19:748-756.
- Nkemdirim, L.C. 1980b. Cold air drainage and temperature fields in an urban environment: a case study of topographical influence on climate. *Atmospheric Environment* 14:375-381.
- Nkemdirim, L.C. 1981. Extra urban and intra urban rainfall enhancement by a medium-sized city. *Water Resources Bulletin* 17:753-759.
- Nkemdirim, L.C. and P.W. Benoit. 1975. Heavy snowfall expectation for Alberta. *Canadian Geographer* 19:60-72.
- Nkemdirim, L.C. and L. Weber. 1976. Wet and dry sequences in precipitation regimes. *Geografiska Annaler* 58A:303-315.
- Nkemdirim, L.C. and K. Leggat. 1978. The effect of chinook weathr on urban heat islands and air pollution. *Water, Air and Soil Pollution* 9:53-67.
- Nkemdirim, L.C. and P. Truch. 1978. Variability of temperature fields in Calgary, Alberta. *Atmospheric Environment* 12:809-822.
- Oke, T.R. 1978. Boundary layer climates. Methuen and Co. Ltd. London, England. 372 pp.
- Olson, R. 1985. The climate of Edmonton. *Climatological Studies* No. 37, *The Climate of Canadian Cities* No. 2. Canadian Climate Program. 55 pp.
- Peters, T.W. 1977. Relationships of yield data to agroclimates, soil capability classification and soils of Alberta. *Canadian Journal of Soil Science* 57:341-347.

- Peterson, E.B., N.M. Peterson, and R.D. Kabzems. 1983. Impact of climatic variations on biomass accumulation in the boreal forest zone: selected references. Prepared by Western Ecological Services (B.C.) Ltd. for Environment Canada, Northern Forest Research Centre. Information Report NOR-X-254. 355 pp.
- Phillips, D.W. (Compiler). 1983. A bibliography of Canadian climate 1977-1981. Environment Canada, Atmospheric Environment Service. 169 pp.
- Postel, S. 1986. Altering the Earth's chemistry: assessing the risks. Worldwatch Institute, Washington, D.C. Worldwatch Paper 71. 66 pp.
- Powell, J.M. 1977. Precipitation climatology of the eastern slopes area of Alberta. In: Proceedings of the Symposium on the Alberta Watershed Research Program. 1977 August 31 to September 01. Edmonton, Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-176. pp. 187-204.
- Powell, J.M. 1978a. Climatic classification of the prairie provinces of Canada. In: Essays on meteorology and climatology: In honour of Richmond W. Longley. Edited by K.D. Hage and E.R. Reinelt. University of Alberta, Department of Geography Monograph 3. Edmonton, Alberta. pp. 211-230.
- Powell, J.M. 1978b. Climatic networks for forestry purposes. In: Climatic networks. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1978 April 13. Edmonton, Alberta. Compiled by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-209. pp. 17-29.
- Powell, J.M. 1981. Impact of climatic variation of boreal forest biomass production. In: Climatic change in Canada 2. Edited by C.R. Harington. National Museum of Natural Sciences, Ottawa, Ontario. Syllogeus No. 33. pp. 189-194.
- Powell, J.M. and D.C. MacIver. 1975. Climatic classifications of the prairie provinces: A new preliminary classification for the forested area of Alberta. In: Western Canadian Research in Geography: The Lethbridge papers. Edited by B.M. Barr. B.C. Geographical Series Number 21. pp. 99-111.
- Powell, J.M. and D.C. MacIver. 1976. Summer climate of the Hinton-Edson area, West-Central Alberta, 1961-1970. Northern Forest Research Centre. Edmonton, Alberta. Information Report NOR-X-149. 43 pp.
- Powell, J.M. and D.C. MacIver. 1977. A summer climate classification for the forested area of the Prairie Provinces using factor analysis. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-177. 51 pp.

- Powell, J.M. and D.C. MacIver. 1978. Maps of selected climatic parameters for the Prairie Provinces, May to September, 1961 to 1970. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-206. 31 pp.
- Rachuk, T. 1977. Climatological aspects of wind and solar energy. In: Applications of climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Edited by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 29-33.
- Reinelt, E.R. 1970. On the role of orography in the precipitation regime of Alberta. Alberta Geographer 6:45-48.
- Rudolph, R.C., M.M. Oleskiw, and R.A. Stuart. 1984. Climatological analysis of recent data from the Athabasca oil sands area. Prepared by Intera Environmental Consultants Ltd. for the Alberta Oil Sands Environmental Research Program. AOSERP Report 130. 199 pp.
- Sadler, G.W. 1970. Measurement of apparent solar constant and apparent extinction coefficient at Edmonton (Alberta) Canada. Solar Energy 13:35-41.
- Sadler, G.W. 1978a. Characteristics of clear sky normal incidence solar insolation measured with the RG2 filter. Solar Energy 20:139-142.
- Sadler, G.W. 1978b. Turbidity of the atmosphere at solar noon for Edmonton, Alberta, Canada. Solar Energy 21:339-342.
- Sadler, G.W. 1981. The attenuation of direct beam solar radiation for the bands defined by the OG1, RG2, and RG8 filters. American Society of Heating, Refrigerating and Air Conditioning Engineers Transactions 87(Part 2):383-395.
- Schweger, C., T. Habgood, and M. Hickman. 1981. Late glacial-holocene climatic changes of Alberta. The record from lake sediment studies. In: The impacts of climatic fluctuations on Alberta's resources and environment. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1981 February 26. Edmonton, Alberta. Compiled by K.R. Leggat and J.T. Kotylak. Environment Canada, Atmospheric Environment Service Report No. WAES-1-81. pp. 47-60.
- Singh, T. 1986. Microclimate of clearcuts in west-central Alberta. In: Current climatological activity in Alberta. Proceedings of the 10th Annual General Meeting of the Alberta Climatological Association. 1986 February 20. Edmonton, Alberta. pp. 47-73.
- Singh, T. and J.M. Powell. 1986. Climatic variation and trends in the boreal forest region of western Canada. Climatic Change 8:267-278.

- Strong, G.S. and E.P. Lozowski. 1977. An Alberta study to objectively measure hailfall intensity. *Atmosphere* 15:33-53.
- Strong, W.L. and K.R. Leggat. 1981. Ecoregions of Alberta. Energy and Natural Resources, Resources Evaluation and Planning Division. ENR Technical Report Number T/4. 64 pp.
- Subcommittee on Biophysical Land Classification. 1969. Guidelines for biophysical land classification. Compiled and edited by D.S. Lacate. Canada Department of Fisheries and Forestry. Forest Service Publication 1264. 55 pp.
- Thyer, N. 1981. Diurnal variations of upper winds in summer in Alberta. *Atmosphere-Ocean* 19:337-344.
- Toogood, J.A. 1978. Meteorological data needed in soil conservation studies in Alberta. In: Climate networks. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1978 April 13. Edmonton, Alberta. Compiled by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-209. pp. 30-33.
- Treidl, R.A. 1978. Climatic variability and wheat growing in the prairies. In: Essays on meteorology and climatology: In honour of Richmond W. Longley. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. Edmonton, Alberta. pp. 347-366.
- Tyndall, J. 1861. On the absorption and radiation of heat by gases and vapours, and on the physical connection of radiation, absorption, and conduction. *Philosophical Magazine and Journal of Science*, Series 4, 22:273-285.
- Verschuren, J.P. and L. Wojtiw. 1980. Estimate of the maximum probable precipitation for Alberta River basins. Prepared for Hydrology Branch, Alberta Environment. RMD Report 80/1. 307 pp.
- Walmsley, J. L., and D. L. Bagg. 1978. A method of correlating wind data between two stations with application to the Alberta oil sands. *Atmosphere-Ocean* 16:333-347.
- Webster, G.R. 1977. Influence of fertilizers, soil nutrients, and weather on barley and forage yields in central Alberta. In: Applications of Climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 65-68.
- Western Research and Development Ltd. 1977. A preliminary study of the effects of the chinook on the air pollutant levels in Calgary. Prepared for Alberta Environment, Research Secretariat. 60 pp.

- Williams, G.D.V. 1985. Estimated bioresource sensitivity to climatic change in Alberta, Canada. *Climatic Change* 7:55-69.
- Williams, G.D.V. and J.M. Masterton. 1983. An application of principal component analysis and an agroclimatic resource index to ecological land classification for Alberta. *Climatological Bulletin* 17:3-28.
- Wojtiw, L. 1975. Climatic summaries of hailfall in Central Alberta (1957-1973). Alberta Research Council, Atmospheric Sciences Department Report 75-1. 102 pp.
- Wojtiw, L. 1977. Climatology of hailstorms in central Alberta. *Albertan Geographer* 13:15-30.
- Wojtiw, L. 1979. Factors affecting hail-crop damage. In: Research, operations, and evaluation in the Alberta hail project 1974-1978. Research-Precipitation Studies. Alberta Research Council, Atmospheric Sciences Department Report 79-1(2-C):57-63.
- Wojtiw, L. 1981. Climatology of hailfalls and hailswaths in Central Alberta, Canada. In: Extended abstracts: Eighth Conference on Inadvertent and Planned Weather Modification. 1981 October 05-07. Reno, Nevada. American Meteorological Association. pp. 134-135.
- Wojtiw, L. 1986a. Radar for rainstorm intensity-duration estimates in central Alberta. Alberta Research Council, Atmospheric Sciences Department Report 86-2. 12 pp.
- Wojtiw, L. 1986b. Time-characteristics of hailfall in central Alberta, Canada. In: Preprint volume: 10th Conference on Planned and Inadvertent Weather Modification. 1986 May 27-30. Arlington, Virginia. American Meteorological Society. pp. 96-99.
- Wojtiw, L. (Compiler). 1986c. A bibliography of weather modification and related topics in Alberta. Alberta Research Council, Atmospheric Sciences Department. 53 pp.
- Wojtiw, L. and J.P. Verschuren. 1981. Climatology of severe rainstorms in Alberta, Canada. In: Preprint Volume: 4th Conference on Hydrometeorology. 1981 October 07-09. Reno, Nevada. American Meteorological Society. pp. 21-26.
- World Meteorological Organization. 1960. Guide to Climatological practices. WMO report No. 100. Geneva, Switzerland. 44 pp.
- World Meteorological Organization. 1983. Guide to meteorological instrument and methods of observation. 5th Edition. Secretariat of the World Meteorological Organization. Geneva, Switzerland. 476 pp. plus Appendices.

- World Meteorological Organization. 1984. The global climate system. A critical review of the climate system during 1982-1984. World Climate Data Programme. Geneva, Switzerland. 52 pp.
- Yap, D. 1975. A preliminary investigation of the nocturnal temperature structure above the City of Edmonton, Alberta. Ontario Ministry of Environment. 25 pp.
- Young, G.J. 1977. Relations between mass-balance and meteorological variables on Peyto Glacier, Alberta, 1967/1974. Zeitschrift für Gletscherkunde und Glazialgeologie 13H:111-125.

7.2 UNCITED REFERENCES

- Alberta. Environment. 1984. Climate of Alberta with data for the Yukon and the Northwest Territories. Report for 1984. Tables of temperature, precipitation, and sunshine. Compiled by Environment Canada, Atmospheric Environment Service. 87 pp.
- Angle, R.P. and J.U. Godin. 1979. A meteorological station for air quality management. Paper presented at the Annual Meeting of the Air Quality Control Association, Pacific Northwest International Section. November 7-9. Edmonton, Alberta. 17 pp.
- Angle, R.P. and J.U. Godin. 1982. Toward an atmospheric boundary layer climatology for central Alberta. In: Current climatological activity in Alberta. Proceedings of the Technical and Business Sessions of the 6th Annual General Meeting of the Alberta Climatological Association. 1982 February 25. Edmonton, Alberta. Compiled by Bill Kuhnke. Alberta Environment. pp. 25-37
- Barge, B.L., R.G. Humphries, S.J. Mah, and W.K. Kuhnke. 1981. Precipitation measurements by weather radar in central Alberta - applications to hydrology. Proceedings of the 7th Symposium of the Water Studies Institute on Applied Prairie Hydrology. 1978 May 9-11. Saskatoon, Saskatchewan. Edited by J. Whiting. pp. 17-25.
- Benfield, R.W. 1980. Climatic considerations in urban and regional planning. In: Socioeconomic impacts of climate. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1979 March 02. Edmonton, Alberta. Compiled by J.M. Powell. Environment Canada, Northern Forest Research Centre. Information Report NOR-X-217. pp. 55-58.
- Caiazza, R., K.D. Hage, and D. Gallup. 1978. Wet and dry deposition of nutrients in central Alberta. Water, Air and Soil Pollution 9:309-314.

- Changnon, S.A. Jr. 1977. Climatology of hail in North America. *Meteorological Monographs* 16:107-128.
- Croft, B.R. 1977. The importance of climatological data to the environmental consultant. In: *Applications of Climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 78-86.*
- Danard, M. and M. Gray. 1982. Modelling the topographic effects on winds in the Alberta oil sands area. Prepared by Atmospheric Dynamics Corporation for Alberta Environment, Research Management Division. AOSERP Report 126. 89 pp.
- Fawkes, P.E. 1979. Probable maximum flood for the Peace River at Site C. In: *Cold climate hydrology. Proceedings of the Canadian Hydrology Symposium '79. 1979 May 10-11. Vancouver, B.C. National Research Council, Associate Committee on Hydrology. pp. 239-250.*
- Ferguson, H.L. and D.W. Phillips. 1986. Developing a national climate program - a decade of Canadian experience. Environment Canada, Atmospheric Environment Service, Canadian Climate Centre. 30 pp.
- Golding, D.L. 1977. Snowpack evaporation during chinooks along the east slopes of the Rocky Mountains. In: *Proceedings of the Second Conference on Hydrometeorology. 1977 October 25-27. Toronto, Ontario. American Meteorological Society. pp. 251-254.*
- Golding, D.L. and R.H. Swanson. 1978. Snow accumulation and melt in small forest openings in Alberta. *Canadian Journal of Forest Research* 8:380-388.
- Government of Canada. 1984. Drought workshop proceedings. Canadian Climate Program Climate Advisory Committee Annual Program Review Meeting. 1983 August 29-30. Regina, Saskatchewan. 131 pp.
- Graham, D.R., W.E. Kerr, and R.J. Grauman. 1978. Hydrometeorological telemetry network of Alberta. In: *Proceedings of the Western Snow Conference 46th Annual Meeting. 1978 April 18-20. Otter Rock, Oregon. pp. 1-6.*
- Gray, J. and P. Thompson. 1976. Climatic information from $\delta^{18}O/\delta^{16}O$ ratio of cellulose in tree rings. *Nature* 262:481-482.
- Gray, J. and P. Thompson. 1977. Climatic information from $\delta^{18}O/\delta^{16}O$ analysis of cellulose, lignin and whole wood from tree rings. *Nature* 270:708-709.
- Hage, K.D. 1977. Research in urban climatology at the University of Alberta. *Climatological Bulletin* No. 22. pp. 25-29.

- Hage, K.D. 1981. Wave-like oscillations in urban valley drainage flow. In: Preprint Volume of Extended Abstracts of the 5th Symposium on Turbulence, Diffusion, and Air Pollution. 1981 March 09-13. Atlanta, Georgia. American Meteorological Society. pp. 179-180.
- Hage, K.D., J. Gray, and J.C. Linton. 1975. Isotopes in precipitation in northwestern North America. *Monthly Weather Review* 103:958-966.
- Hare, F.K. 1980. Climate and agriculture - the uncertain future. *Journal of Soil and Water Conservation* 35:113-115.
- Harris, S.A. 1979. Ice caves and permafrost zones in southwest Alberta. *Erdkunde* 33:61-70.
- Harris, S.A. 1981. Climatic relationships of permafrost zones in areas of low winter snow-cover. *Arctic* 34:64-70.
- Harris, S.A. and R.J.E. Brown. 1978. Plateau Mountain: a case study of alpine permafrost in the Canadian Rocky Mountains. In: *Proceedings of the 3rd International Conference on Permafrost*. 1978 July 10-13. Edmonton, Alberta. National Research Council 1:385-391.
- Hawrelak, J., T. Rachuk, and J. Barlishen. 1976. Wind power in Alberta. Prepared by Alberta Research Council and Alberta Environment, Planning Division. 110 pp.
- Hay, J.E. and P.W. Suckling. 1979. An assessment of the networks for measuring and modelling solar radiation in British Columbia and adjacent areas of western Canada. *The Canadian Geographer* 23:222-238.
- Hayter, R. and V.B. Proudfoot. 1978. Frost in northeast central Alberta. In: *Essays on Meteorology and Climatology in Honour of Richmond W. Longley*. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. pp. 95-118.
- Hennie, H.H. 1977. Human response to floods - Alberta experiences. In: *Proceedings of the Canadian Hydrology Symposium '77*. 1977 August 29-31. Edmonton, Alberta. National Research Council, Associate Committee on Hydrology. pp. 88-89.
- Hillman, G.R., J.M. Powell, and R.L. Rothwell. 1978. Hydrometeorology of the Hinton-Edson area, Alberta, 1972-1975. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-202. 171 pp.

- Howell, D.G. 1979. Processing of Alberta wind data and its applications to wind energy system design. In: Solar energy: bringing it down to earth. National Conference '79 of the Solar Energy Society of Canada. August 1979. Charlottetown, Prince Edward Island. Paper No. 79-6. 11 pp.
- Howell, J.D. and S.A. Harris. 1978. Soil-forming factors in the Rocky Mountains of southwestern Alberta. Arctic and Alpine Research 19:313-324.
- Janz, B. 1976. Synoptic patterns associated with heavy spring snowfalls in southwestern Alberta. In: Proceedings of the Western Snow Conference 44th Annual Meeting. 1976 April 20-22. Calgary, Alberta. pp. 48-55.
- Kerr, W.E., G.W. Guenther, and D.W. Miller. 1975. Alberta 1974-75 snow survey. Alberta Environment, Technical Services Division. Technical Report No. 24. 70 pp.
- Kiil, A.D., R.S. Miyagawa, and D. Quentilio. 1977. Calibration and performance of the Canadian fire weather index in Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Report NOR-X-173. 45 pp.
- Kite, G.W. and I.A. Reid. 1977. Volumetric change of the Athabasca glacier over the last 100 years. Journal of Hydrology 32:279-294.
- Kojima, S. and G.J. Krumlik. 1979. Biogeoclimatic classification of forests in Alberta. The Forestry Chronicle 55:130-132.
- Kotylak, J.T. 1978. National standards in weather observing networks. In: Climatic networks. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1978 April 13. Edmonton, Alberta. Compiled by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-209. pp. 2-8.
- Leahey, D.M. 1975. An application of a simple advective pollution model to the city of Edmonton. Atmospheric Environment 9:817-823.
- Lester, P.F. 1978. A lee wave cloud climatology for Pincher Creek, Alberta. Atmosphere-Ocean 16:157-168.
- Longley, R.W. 1975. Precipitation in valleys. Weather 30:294-300.
- Longley, R.W. 1977. Applications of climatology. In: Applications of climatology. Proceedings of the Workshop and Annual Meeting sponsored by the Alberta Climatological Committee. 1977 March 04. Edmonton, Alberta. Edited by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-193. pp. 5-10.

- Longley, R.W. 1980. The climate of Alberta. In: A nature guide to Alberta. Edited by D.A.E. Spalding. Provincial Museum of Alberta Publication No. 5. pp. 26-28.
- Luk, S-H. 1978. Soil erodibility in southern Alberta. *Geografiska Annaler* 60A:143-149.
- McKay, G.A. 1978. Climatic change and the Canadian economy. In: Essays on meteorology and climatology: In honour of Richmond W. Longley. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. pp. 151-170.
- Meeres, L.S. 1977. A preliminary study of changes in wind structure produced by a commercial-appearing cut in mature forest. In: Proceedings of the Symposium on the Alberta Watershed Research Program. 1977 August 31 to September 01. Edmonton, Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-176. pp. 220-236.
- Mustapha, A.M., G.W. Samide, and W.K. Kuhnke. 1976. Flood forecasting - Oldman River basin. In: Proceedings of the Western Snow Conference 44th Annual Meeting. 1976 April 20-22. Calgary, Alberta. pp. 101-105.
- Mustapha, A.M., S. Figliuzzi, H. Rickert, and G. Coles. 1981. History of floods in the North Saskatchewan River basin. Alberta Environment, Technical Services Division. 125 pp.
- Nemanishen, W. 1981. Some evidence of hydrometeorological cycles in east slopes data and its usefulness in water resources management. In: The impacts of climatic fluctuations on Alberta's resources and environment. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1981 February 26. Edmonton, Alberta. Compiled by K.R. Leggat and J.T. Kotylak. Environment Canada, Atmospheric Environment Service. Report No. WAES-1-81. pp. 2-22.
- Nkemdirim, L.C. 1976. Crop development and water loss - a case study over a potato crop. *Agricultural Meteorology* 16:371-388.
- Nkemdirim, L.C. 1981. Cloudiness and wind speed as factors in a climate anomaly. *Tellus* 33:12-18.
- Nkemdirim, L.C., G.R. Lunn, and R.D. Rowe. 1975. Pollutant concentration and stratification in urban heat island. *Water, Air and Soil Pollution* 4:99-112.
- Owen, J.A. and D.R. Nancarrow. 1977. Flooding in the city of Calgary. In: Proceedings of the Canadian Hydrology Symposium '77. 1977 August 29-31. Edmonton, Alberta. National Research Council, Associate Committee on Hydrology. pp. 99-110.

- Phillips, D.W. and G.A. McKay (Editors). 1981. Canadian climate in review - 1980. Environment Canada, Atmospheric Environment Service. 104 pp.
- Powell, J.M. 1976. A directory of climate and related courses and persons interested in climatology in Alberta. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-172. 63 pp.
- Powell, J.M. 1983. Richmond Longley and climatic and variability in Canada. In: Climatic change in Canada 3. Edited by C.R. Harington. National Museum of Natural Sciences. Ottawa, Ontario. Syllogeus No. 49. pp. 337-343.
- Powell, J.M. and D.C. MacIver. 1975. A factor analytic climatic classification of the forested areas of the prairie provinces. In: Proceedings of the 12th Agricultural Meteorology Conference. 1975 April 14-16. Tucson, Arizona. American Meteorological Society.
- Powell, J.M. and D.C. MacIver. 1978. Maps of selected climatic parameters for the prairie provinces May to September 1961-1970. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-206. 31 pp.
- Reynolds, David C. 1979. The air pollution potential of Kananaskis Valley. Atmosphere-Ocean 17:22 (Abstract only).
- Rowe, R.D. 1980. A simple two-layer model for stable air flow across terrain features. Paper presented at 2nd Joint Conference on Applications of Air Pollution Meteorology. 1980 March 24-27. New Orleans, Louisiana. American Meteorological Society. pp. 559-566.
- Rudolph, R.C. and K.D. Hage. 1983. Potential flow model of pollutant recirculation in a small valley. Archives for Meteorology, Geophysics and Bioclimatology B33:175-185.
- Sewell, W.R.D. and D. MacDonald-McGee. 1983. Climate variability and change in Canada towards an acceleration of the social science research effort. Canadian Climate Planning Board. Ottawa. 41 pp.
- Steed, G.L. 1978. Climatological requirements for a regional hydrologist. In: Climatic networks. Proceedings of the Workshop and Annual Meeting of the Alberta Climatological Association. 1978 April 13. Edmonton, Alberta. Compiled by J.M. Powell. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-209. 101 pp.
- Steed, G L. 1982. Climatic trends of South Alberta. A summary report. Prepared for Alberta Environment, Technical Services Division. 51 pp.

- Storr, D. and G. Den Hartog. 1975. Basin water balance studies in the Rocky Mountains and foothills of Alberta. In: Proceedings of the Canadian Hydrology Symposium. 1975 August 11-14. Winnipeg, Manitoba. pp. 436-447.
- Storr, D. and D.L. Golding. 1976. Comparison of precipitation-gauge and snow pillow data from a severe April snowstorm in a mountain watershed. In: Proceedings of the Western Snow Conference 44th Annual Meeting. 1976 April 20-22. Calgary, Alberta. pp. 78-86.
- Strong, G.S. and M.L. Khandekar. 1975. A note on fluctuations in the normal temperature trend at selected Canadian stations. Atmosphere 13:19-25.
- Swanson, R.H. 1980. Surface wind structure in forest clearings during a chinook. Proceedings of the Western Snow Conference. 1980 April 15-17. Laramie, Wyoming. pp. 26-30.
- Suckling, P.W. and J.E. Hay. 1976. The spatial variability of daily values of solar radiation for British Columbia and Alberta. Climatological Bulletin No. 20. pp. 1-7.
- Thomas, M.K. 1978. Canadian Climatological Literature 1768 - 1957. In: Essays on Meteorology and Climatology in Honour of Richmond W. Longley. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. pp. 329-346.
- Thomas, M.K. and D.W. Phillips (Compilers). 1979. A bibliography of Canadian climate 1972-1976. Environment Canada, Atmospheric Environment Service. 135 pp.
- Thompson, W.C. 1976. Three early severe flood producing storms in Alberta. Environment Canada, Atmospheric Environment Service TEC-827. 10 pp.
- Walker, B.D., S. Kojima, W.D. Holland, and G.M. Coen. 1978. Land classification of the Lake Louise study area, Banff National Park. Fisheries and Environment Canada, Northern Forest Research Centre. Information Report NOR-X-160. 121 pp.
- Whelpdale, D.M. and L.A. Barrie. 1982. Atmospheric monitoring network operations and results in Canada. Water, Air and Soil Pollution 18:7-23.
- Wiersma, G.B. 1984. Integrated global background monitoring network. Paper presented at the Symposium on Research and Monitoring in Circumpolar Biosphere Reserves. 1984 August 27-31. Waterton, Alberta. 31 pp.
- Wiggins, E.J. 1978. Prospects for solar and wind energy utilization in Alberta. Alberta Energy and Natural Resources Report No. 89. 101 pp.

- Williams, G.D.V., M.I. Joynt, and P.A. McCormick. 1975. Regression analysis of Canadian prairie crop-district cereal yields, 1961-72, in relation to weather and soil trend. *Canadian Journal of Soil Science* 55:43-52.
- Williams, G.D.V. and W.D. Oakes. 1978. Climatic resources for maturing barley and wheat in Canada. In: *Essays on meteorology and climatology: In honour of Richmond W. Longley*. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. pp. 367-386.
- Williams, G.D.V., J.S. McKenzie, and M.I. Sheppard. 1980. Mesoscale agroclimatic resource mapping by computer, an example for the Peace River region of Canada. *Agricultural Meteorology* 21:93-109.
- Wilson, H.P. 1978. Chinook airflow. In: *Essays in meteorology and climatology in honour of Richmond W. Longley*. Edited by K.D. Hage and E.R. Reinelt. The University of Alberta, Department of Geography Monograph 3. pp. 387-398.
- Wojtiw, L. 1975. Hailfall and crop damage in central Alberta. *Journal of Weather Modification* 7:28-42.
- Wojtiw, L. 1975. Climatology of hailstorms in Alberta. In: *National Hail Research Experiment Symposium-Workshop on Hail*. National Center for Atmospheric Research. Boulder, Colorado. Preprint I, Section II. pp. C1.1-C1.14.
- Wojtiw, L. and E.P. Lozowski. 1975. Record Canadian hailstones. *Bulletin of the American Meteorological Society* 56:1275-1276.
- Won, T.K. 1977. The simulation of hourly global radiation from hourly reported meteorological parameters - Canadian prairie area. In: *Solar energy update '77. Proceedings of the 3rd Conference of the Solar Energy Society of Canada*. 1977 August 22-24. Edmonton, Alberta. Paper E40-M-pm25. 23 pp.
- Young, G.J. 1981. The mass balance of Peyto Glacier, Alberta, Canada, 1965 to 1978. *Arctic and Alpine Research* 13:307-318.